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Electric Measurements Lamps and Heating

213 Illustrations

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ALTERNATING-CURRENT MEASURING INSTRUMENTS
WATT-HOUR METERS
VOLTAGE REGULATION OF ALTERNATING CURRENT CIRCUITS
ELECTRIC LAMPS
ELECTRIC HEATING

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PREFACE

The volumes of the International Library of Technology are made up of Instruction Papers, or Sections, comprising the various courses of instruction for students of the International Correspondence Schools. The original manuscripts are prepared by persons thoroughly qualified both technically and by experience to write with authority, and in many cases they are regularly employed elsewhere in practical work as experts. The manuscripts are then carefully edited to make them suitable for correspondence instruction. The Instruction Papers are written clearly and in the simplest language possible, so as to make them readily understood by all students. Necessary technical expressions are clearly explained when introduced.

The great majority of our students wish to prepare themselves for advancement in their vocations or to qualify for more congenial occupations. Usually they are employed and able to devote only a few hours a day to study. Therefore every effort must be made to give them practical and accurate information in clear and concise form and to make this information include all of the essentials but none of the non-essentials. To make the text clear, illustrations are used freely. These illustrations are especially made by our own Illustrating Department in order to adapt them fully to the requirements of the text.

In the table of contents that immediately follows are given the titles of the Sections included in this volume, and under each title are listed the main topics discussed. At the end of the volume will be found a complete index, so that any subject treated can be quickly found.

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ALTERNATING-CURRENT MEASURING INSTRUMENTS

DESCRIPTION OF INSTRUMENTS

CLASSIFICATION

1. Measuring instruments of the moving-iron, electrodynamometer, electrostatic, and hot-wire type described in *Direct-Current Measuring Instruments* are also employed for alternating-current measurements. Instruments of the *induction type* and *vibrating type* are suitable for alternating-current operation only.

Alternating-current instruments include ammeters, voltmeters, wattmeters, power-factor meters, frequency meters, phase indicators, synchroscopes, and oscillographs. Indicating, recording, and integrating instruments are available.

INDUCTION INSTRUMENTS

GENERAL THEORY OF ACTION

2. Induction type instruments are so called because their operation depends on current induced in a movable system, or element, by a revolving or gliding magnetic flux set up by the stationary element. The movable element is usually a disk or a cylinder of metal balanced by either gravity or a spring and

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carrying a pointer or a pen. The revolving flux is produced in single-phase and polyphase instruments by methods similar to those employed for corresponding motors.

SHADED-POLE AMMETERS

3. Description and Operation.—In Fig. 1 is shown the exterior of an induction type ammeter and in Fig. 2 the general arrangement of the interior parts.

The current to be measured traverses the exciting coil *a* and its shunt *b* and sets up an alternating flux in the laminated core *c*. The shading coils *d* on the pole pieces of this core cause the included part of the flux to lag behind the flux from the remainder of the pole face, thus setting up a gliding flux that reacts with the induced currents in the aluminum disk *e* and causes the latter to rotate. The disk is mounted on a shaft *f*, to which is also attached a pointer *g* and a control spring *h*. The disk rotates until its turning force is balanced by the spring tension, and the pointer then rests over the figure on the scale indicating the current.

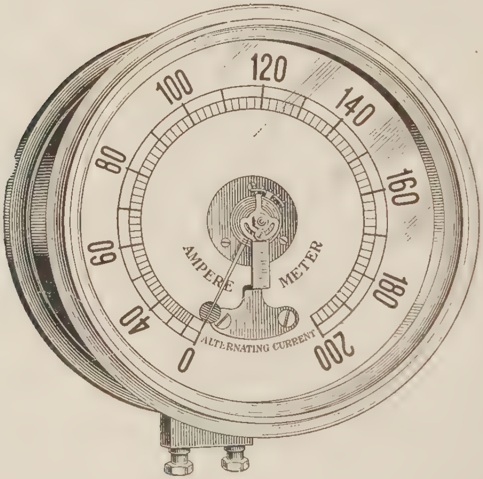

Fig. 1

The disk also rotates between the poles of a permanent magnet *i*, which acts as a damper. Rapid movements cause eddy currents in the disk near the poles of the permanent magnet, and the reactions of currents and flux bring the needle promptly to rest. As the eddy currents exist only while the disk is in motion, they do not interfere with the accuracy of the final reading.

4. Compensating Devices.—The disk *e*, Fig. 2, is so shaped that the change in deflection for a given change of current is very nearly the same on all parts of the scale; that is, all the scale divisions have approximately the same length.

The shunt *b* permits the use of small wire in coil *a* and also compensates for changes of temperature. This shunt is made of nickel, the resistance of which increases with increased temperature more rapidly than that of copper. The proportional part of the main current that passes through coil *a* is thus increased. The increased temperature increases the resistance of disk *e* also, and thus reduces the eddy currents in it. The increased current in coil *a* compensates for the decreased eddy currents in the disk. At any current, the turning effort on the disk is therefore practically constant at all temperatures.

The shunt *b* is non-inductive and the coil *a* is inductive. The higher the frequency, therefore, the less will be the proportional part of the current carried by the coil *a*. This decrease in current carried by the exciting coil compensates for the increased eddy currents that would occur in the disk at the higher frequency if the current had not been changed. The instrument is therefore compensated for change in frequency of the circuit under test.

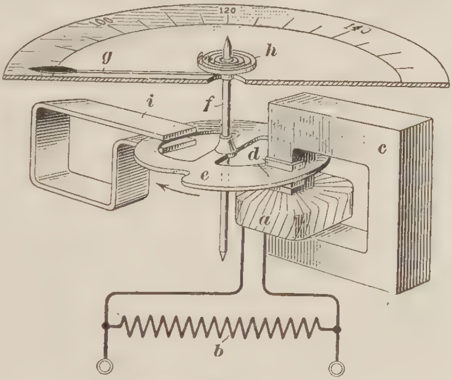

FIG. 2

SHADED-POLE VOLTMETERS

5. The **shaded-pole voltmeter** employs the same principles of operation as the ammeter. The exciting coil *a*, Fig. 3, has many turns of fine wire and has not only a non-inductive nickel shunt *b* but also a coil *c* of high inductance in series. The shunt performs the same functions as in the ammeter, and the series coil assists in compensating for changes in frequency. At high frequency, the current through the exciting coil *a* decreases enough to compensate for the effect of the increased eddy currents that would otherwise occur in the disk.

SPLIT-PHASE AMMETERS AND VOLTMETERS

6. A **split-phase instrument** has two separate windings, the coils of which are displaced in position. The inductance of one winding is made greater than that of the other, thus causing a phase difference between the currents in the two windings. A revolving flux is set up, causing eddy currents in a pivoted drum or disk and resulting in rotation of the drum, the action being similar to that of a single-phase induction motor with a split-phase starting arrangement.

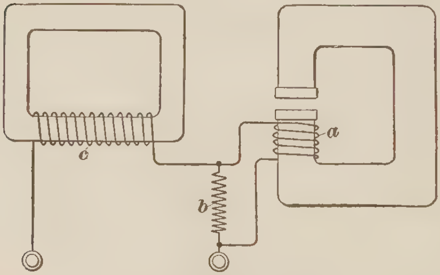

FIG. 3

Ammeters and voltmeters are made in which this split-phase construction is employed. The current coils of ammeters consist of comparatively coarse wire, and the pressure coils of voltmeters of comparatively fine wire. If the current or the voltage is high, a current or a voltage transformer is employed to reduce the quantity to a value suitable for the instruments.

INDUCTION AMMETERS AND VOLTMETERS

7. In Fig. 4 is shown the arrangement of parts in a typical **induction ammeter** or **voltmeter**. At *a* is shown the main winding that forms the two outside primary coils on the frame of the magnet. The secondary winding consists of the two inner coils *b*, and this circuit is closed through auxiliary magnetizing coils *c* wound in slots in the pole faces. Coils *a* and *b* form the primary and secondary coils of a transformer. The secondary current in coils *c* sets up fluxes differing in phase from the flux, due to the combined action of coils *a* and *b*. Thus, there is set up a revolving flux that induces eddy currents in the metal drum *d*, and the interactions of the revolving flux and the eddy currents cause the drum and its attached pointer *e* to turn to a point where the magnetic forces are balanced by the force of the control spring.

In an ammeter, the primary winding is connected in series with the circuit, and in the voltmeter the primary winding is connected in series with a resistor across the circuit.

INDUCTION WATTMETERS

8. In Fig. 5 is shown the general arrangement of the windings on an **induction wattmeter.** The two current coils *a* are mounted in deep slots in the pole faces and have low inductance. The potential coils *b* have high inductance and are in series with a reactor *c*. Compensating coils *d* are inside the coils *b* and are connected in a closed circuit by an adjustable resistance *e*. Coils *d* and resistor *e* act as a secondary circuit

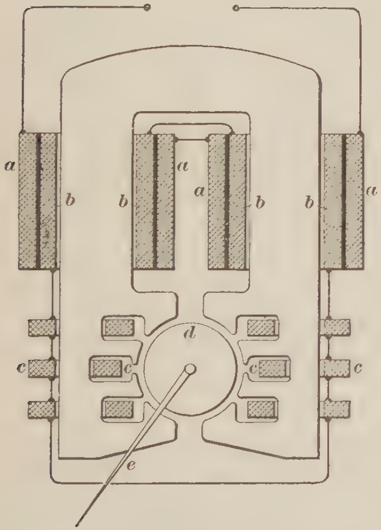

FIG. 4

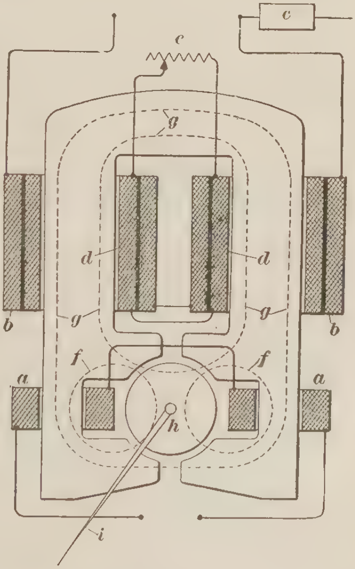

FIG. 5

of a transformer, the primary circuit of which consists of coils *b*. Coils *d* assist coils *b* in producing the proper phase relation between the flux *f* due to the current coils *a*, and the flux *g* due to the combined action of the potential coils *b* and the compensating coils *d*. Flux *f* is nearly in phase with the current in the current coils, and because of the combined action of the potential coils and compensating coils flux *g* lags 90° from the line pressure. A revolving flux is thereby established, eddy currents are induced in drum *h*, and the drum and its pointer *i* turn to a position in which the magnetic forces are balanced by the force of the control spring (not shown).

The phase relation of the fluxes is such that at any power factor the instrument measures the true watts of the circuit to which it is connected.

INDUCTION FREQUENCY METERS

9. In Fig. 6 is shown the exterior of an **induction frequency meter,** and in Fig. 7, the general arrangement of the parts. Two laminated soft-iron magnets *a* and *b* are provided with shading rings *c* and exciting coils *d* and *e*. Coil *d* is in series with a resistor *f* and coil *e* is in series with a reactor *g*, thus causing a phase difference of the currents and fluxes of coils *d* and *e*. The interactions between these fluxes and the eddy currents they set up in the disk *h* cause opposite torques, the action of magnet *a* tending to rotate the disk clockwise and that of magnet *b* counter-clockwise. The circuits of coils *d* and *e* are connected in parallel across the main line wires.

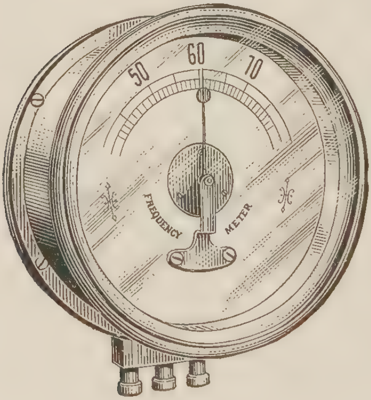

FIG. 6

At normal frequency, the torques balance when the disk is in its middle position. The inductances of the two circuits are unlike, and any change in frequency causes a variation of the impedances of the circuits, a change in the exciting currents in coils *d* and *e*, and an unbalancing of the torques. If the disk were circular, a continuous motion of the disk would be set up; but the disk is so shaped that while the area affected by magnet *a* is constant as the disk turns, the area affected by magnet *b* is decreased if the current in coil *e* is increased, and increased if the current in the coil is decreased. The disk therefore moves to a position in which the torque exerted by magnet *a* is again balanced by the torque exerted by the magnet *b* on the changed area of the disk near it. Any change in frequency causes an unbalancing of the torques on the sides of the disk, and the disk moves to a new position where the torques are again balanced. No control spring is used. A pointer *i* indicates the reading on a scale.

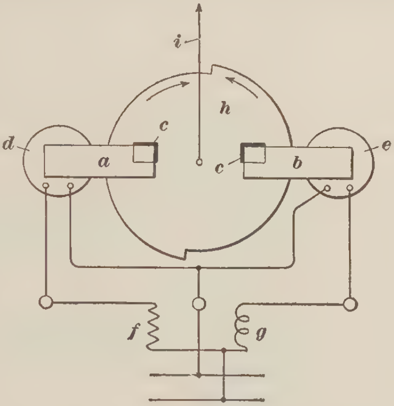

FIG. 7

VIBRATING-REED INSTRUMENTS

FREQUENCY METERS

10. In Fig. 8 is shown the exterior of a **vibrating-reed type frequency meter,** and in Fig. 9, the operating portion of the instrument. A number of steel reeds *a* are mounted near a magnet *b*. The exciting coil *c* of the magnet in series with a resistor is connected across the circuit. The alternating current produces an alternating magnetic flux in the frame and the poles of the magnet and tends to attract the reeds toward the pole piece twice during a cycle, or once for each alternation.

If a strip of steel fastened at one end is bent over and then released, the strip will vibrate at a constant rate, known as its *natural frequency of vibration.*

The reeds in the meter have different natural frequencies of vibration; therefore, the magnet, when energized by an alternating current of a certain frequency, will cause an extended movement of only one or two reeds that most nearly correspond in natural frequency of vibration with the electric frequency of the circuit. The natural vibration of the other reeds will be opposed to a greater or less extent by the periodic attraction of the magnet, and consequently will vibrate but little.

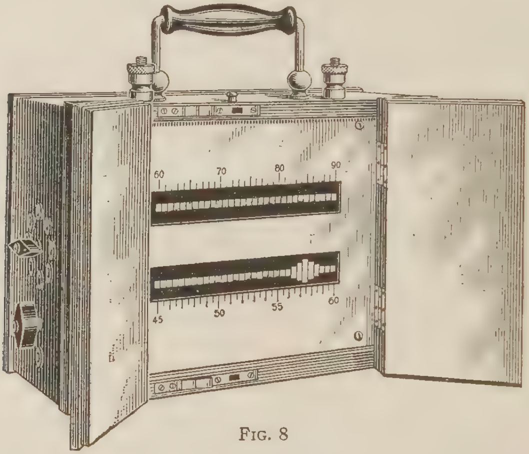

Fig. 8

The frequency of the circuit is indicated by the large vibration of one of the reeds, and the value of the frequency in cycles or alternations is read from the scale, Fig. 8. If the frequency changes, one of the other reeds will be set into violent vibration.

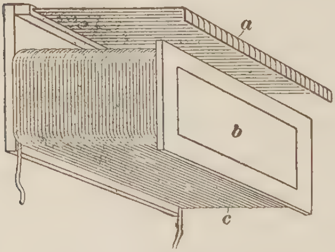

Fig. 9

SPEED INDICATORS

11. As the frequency of an alternator depends on the number of its poles and on the speed of rotation of its moving part, the scale of a frequency meter may be marked to indicate the number of revolutions per minute of the alternator, and the meter used as a **speed indicator.**

MOVING-IRON INSTRUMENTS

FREQUENCY METERS

12. In Fig. 10 is shown a **moving-iron-type frequency meter** with its cover removed, and in Fig. 11, the connections of the parts of this instrument. Two fixed coils *a* and *b*, Figs. 10 and 11, are mounted at right angles to each other, and each coil is wound in two sections (the lower section of coil *a* is not shown in Fig. 10). The moving part of the instrument is an iron needle *c*, Fig. 11, that is free to turn within the coils and is mounted on a shaft that also supports a pointer and an air damper vane. No control spring is used.

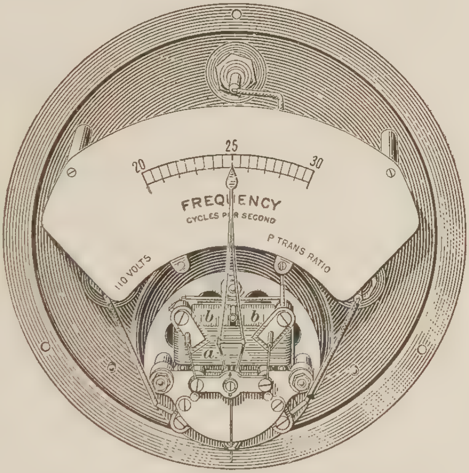

Fig. 10

The reactor *d*, the coil *b*, the coil *a*, and the resistor *e* are connected in series and form one current path of a Wheatstone bridge. The resistor *f* and the reactor *g* form the other path of the bridge. The bridge connections and the reactor *h* are connected in series across the line. There is a connection *i* between the junction of coils *b* and *a* and the junction of resistor *f* and reactor *g*. This connection corresponds to the galvanometer connection in the Wheatstone bridge as applied to resistance measurements.

If the frequency of the circuit changes, the impedances of the reactors change, but the resistances of the resistors do not change appreciably. At a certain frequency, the bridge is balanced and no current passes through wire *i*. The same current passes through coil *a* as through coil *b*, the fluxes are equal, and the needle *c* takes a position where its length is parallel to the resultant flux, as shown in Fig. 11. If the frequency changes, the bridge is unbalanced because of the changes in the values of the impedances of the reactors. Current now passes through wire *i*, the currents in coils *a* and *b* differ, the resultant flux changes its position, and the needle *c* and its pointer assume new positions. Any further change in frequency varies the amount of unbalancing of the bridge and the pointer assumes a new position. The scale, Fig. 10, is marked to read in cycles per second.

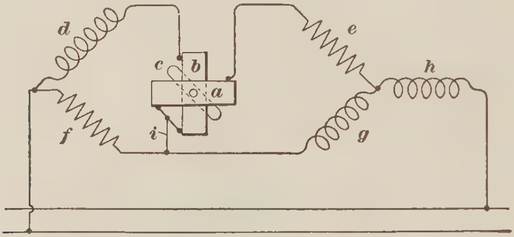

Fig. 11

ELECTRODYNAMOMETER INSTRUMENTS

POWER-FACTOR METERS

13. Single-Phase Meters.—In Fig. 12 is shown a **power-factor meter** of the electrodynamometer type with the cover removed. The connections of the coils are indicated in Fig. 13. The fixed coil *a* is connected in series with one line wire of the circuit, or to a current transformer. The two movable coils *b* and *c*, mounted on a shaft *d* and placed at right angles to each other, are connected in parallel across the circuit, or to the terminals of a potential transformer. A resistor *e* is in series with coil *b*, and a reactor *f*, in series with coil *c*.

The current in coil *b* is in phase with the voltage of the line, and the current in coil *c* lags 90° from the voltage. At unity power factor, the currents in coils *b* and *a* are in phase and the movable system turns so that the fluxes of coils *b* and *a* agree in direction. As the currents are alternating, the fluxes of coils *b* and *a* alternate in direction, but at unity power factor they pass through zero at the same instant and, therefore, the torque is maintained in one direction. The fluxes of coils *c* and *a* differ in phase by 90°, and there is just as much tendency during a cycle to turn coil *c* one way as the other. The action of coil *b* therefore determines the position of the movable system at unity power factor.

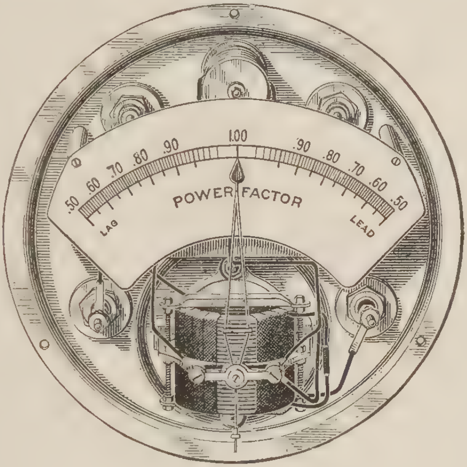

Fig. 12

If the line current differs in phase by 90° from the voltage, the fluxes of coils *c* and *a* are in phase and coil *c* turns the movable system to a position of 90° from that shown in Fig. 13. It may turn to either the right or the left, depending on whether the current leads the line voltage or lags behind it.

When the power factor is between unity and zero, the interactions of the three fluxes are such that the movable system takes up some position less than 90° from its unity power-factor position.

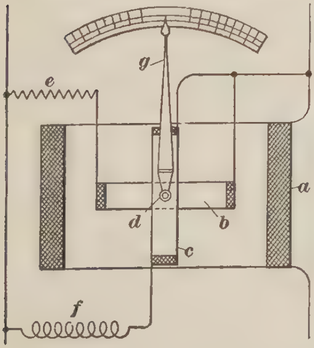

Fig. 13

The action of the instrument may also be considered as follows: A revolving magnetic flux is set up by the currents in coils *b* and *c* and the torque at any power factor is such as to turn the movable system to a position where the revolving flux is at right angles to the axis of coil *a* at the instant that there is no current in coil *a*. Just before this instant, the upper end of coil *a* is of a certain polarity, and immediately afterwards the lower end of the coil is of the same polarity. At this position of the movable system, the rotative tendencies in opposite directions during a cycle are balanced, and the system remains at rest until the phase relation of the current and voltage again changes. The pointer *g* mounted on shaft *d* indicates power factors.

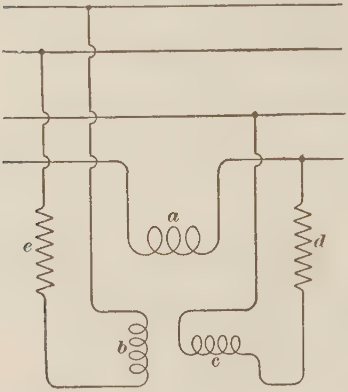

FIG. 14

As a reactor is used, single-phase meters must be employed only on circuits of the frequency for which they were adjusted.

14. Polyphase Meters.—In Fig. 14 are shown the connections of a **two-phase power-factor meter** of the electrodynamometer type. The fixed coil is shown at *a*; the two movable coils mounted at right angles to each other are shown at *b* and *c*, and resistors, at *d* and *e*. The currents in coils *b* and *c* differ in phase by 90° because of their connection to the two phases of the circuit. The action of the meter is therefore similar to that of the single-phase meter, in which the split-phase method is used to produce the required phase relation of the currents.

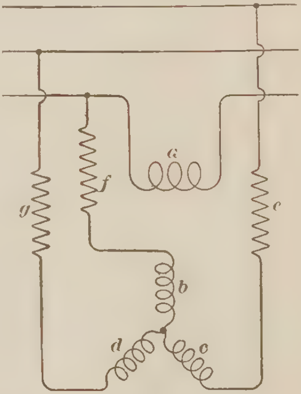

FIG. 15

15. In Fig. 15 are shown the connections of a **three-phase power-factor meter.** The fixed coil is shown at *a*; the movable coils are shown at *b*, *c*, and *d*, and resistors, at *e*, *f*, and *g*. The currents in coils *b*, *c*, and *d* differ in phase relation by 120°, resulting in a revolving magnetic flux. The interaction between the revolving flux and the alternating flux of the fixed coil causes the instrument to indicate the average power factor of the three-phase circuit.

INDICATORS OF THE REACTIVE POWER OF A CIRCUIT

16. Single-Phase Indicators.—On switchboards, **idle-current wattmeters**, or *idle power meters*, are sometimes used to indicate, in watts, the reactive power of a circuit, that is, the product of the amperes, the volts, and the sine of the angle of lag or lead of the current

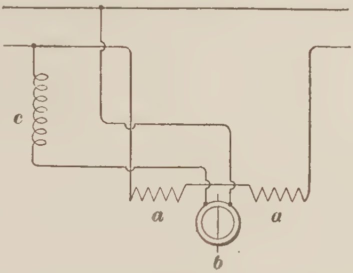

FIG. 16

A single-phase wattmeter of the electrodynamometer type may be arranged to act as an indicator of reactive power. The connections are as shown in Fig. 16, in which the current coils are indicated at *a* and the potential coil is shown at *b*. The potential circuit is made highly inductive by including in that circuit a reactor *c* instead of the usual resistor. At unity power factor, the current in the potential coil differs by nearly 90° from the current in the current coil. In this case, therefore, there is, during a cycle, a balance of the opposing rotational tendencies acting on the movable coil. The coil does not turn, nor does the pointer indicate any watts on the scale. Under these conditions, there is no reactive power.

If the line current lags behind the voltage, the currents in the two coils differ by less than 90°, and there is a component of the current, equal to the product of the current and the sine of the angle of lag, that is in phase with the current in the potential coil; therefore, the interaction of the corresponding fluxes turns the movable coil and the pointer indicates a reading.

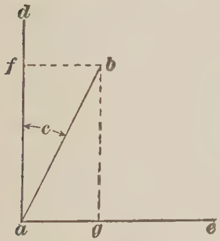

FIG. 17

17. Fig. 17 indicates the phase relation of the magnetic fluxes when the flux *a b* due to the main current lags by angle *c* from the line voltage *a d*, and the flux *a e* of the potential coil lags 90° from the line voltage. The component of the flux of the current coil that is in phase with the flux of the potential coil and therefore active in producing torque, is $f\,b = a\,g = a\,b$ sin c. The torque is, therefore, proportional to the reactive power $E\,I$ sin c, in which E is the line voltage, I the main current, and c the angle of lag of the current. At unity power factor, angle c is zero; there is no component of $a\,b$ that is in phase with $a\,e$, and there is no torque on the movable coil. The greater the angle of lag, represented by the angle c, the greater the torque and the reading of the instrument for given values of voltage and current.

18. Reactive Power Indicators on Polyphase Circuits.—In Fig. 18 are shown the connections of a single-phase

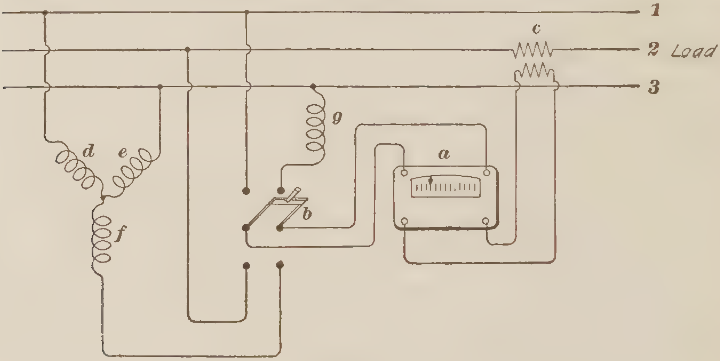

FIG. 18

wattmeter to a balanced three-phase circuit so arranged that the instrument may be used either as a wattmeter or as a reactive power indicator. At a is shown the wattmeter; at b, a double-pole, double-throw switch; at c a current transformer with its secondary in series with the current coil of the wattmeter; and at d, e, f, and g are shown resistors. The resistors d, e, and f are arranged to form a neutral point of the three-phase circuit.

When the switch is in its lower position, the wattmeter indicates the true watts of the three-phase circuit, the scale being marked for this purpose.

When the switch is in its upper position, the potential coil is connected across the line wires *1* and *3* and the current coil terminals remain connected to current transformer c, the primary of which is in series with line wire *2*. Under these conditions and because of the phase relations of the currents in a balanced three-phase circuit of unity power factor, as explained in *Alternating Currents*, Part 2, the current in the potential coil and the current in the current coil differ in phase relation by 90°. The pointer of the meter will therefore not show a reading for unity power factor, but it will show a reading if the current lags from the line voltage.

The scale is so marked that the reading indicates the idle watts for the balanced three-phase circuit.

WATTMETERS

19. Single-Phase Wattmeters.—A wattmeter of the electrodynamometer type may be used for either direct-current or alternating-current measurements. The potential circuit is nearly non-inductive. The indication of the wattmeter is the

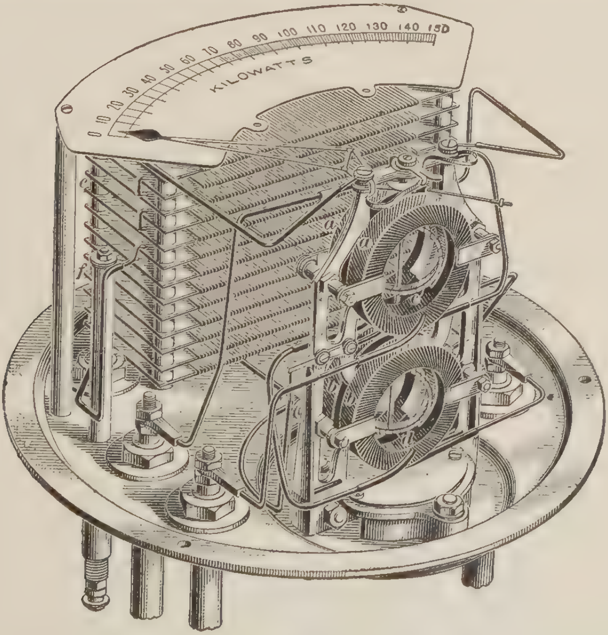

FIG. 19

true watts; that is, it is the product of the voltage, the current, and the cosine of the angle of lag of the current.

At unity power factor, the flux of the current coil and the flux of the potential coil are in phase, and the maximum reading for a given current and voltage is obtained. When the current lags from the line voltage, only a component of the flux of the current coil is in phase with the flux of the potential coil, and this component is equal to the product of the whole flux of the coil and the cosine of the angle of lag a of the current. The component flux is proportional to that part of the main current I which is in phase with the voltage, and the flux of the potential coil is proportional to and in phase with the voltage E; therefore, the meter indicates the true watts of the current, or $E\ I \cos a$.

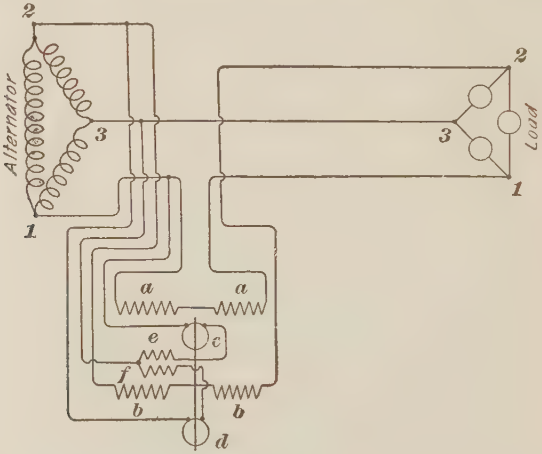

FIG. 20

20. Polyphase Wattmeters.—A single wattmeter may be designed so that it will indicate directly the watts of an unbalanced polyphase circuit. Fig. 19 shows a polyphase wattmeter of the electrodynamometer type consisting of two single-phase elements. The two sets of current coils are shown at a and b; the two potential coils mounted on the same shaft, at c and d; and the resistors for the potential-coil circuits, at e and f. The construction is essentially the same for either two-phase or three-phase wattmeters.

When the instrument is used on a two-phase circuit, one element is connected with each phase, the current coil in series and the potential coil and its resistor across the phase. The pointer indicates the total watts of the two-phase system.

21. In Fig. 20 are shown the connections of the meter to a three-phase system. The letters in Figs. 19 and 20 refer to similar parts. The current and potential coils must be connected in a definite order with reference to each other. Each set of current coils is connected in series with a different line wire, as *1* and *2*. One terminal of each of the potential coils is connected to the same line wire as its current coil and the remaining terminals are connected through resistors *e* and *f* to the line wire *3*.

With these connections, the energy in phase *1–3* influences coils *a* and *c*; the energy in phase *3–2* influences coils *b* and *d*; and the energy in phase *2–1* influences all the coils, because the current of this phase divides between the two sets of current coils *a* and *b* and the voltage of this phase is impressed on the two potential coils *d* and *c* and their resistors, which are in series across line wires *2* and *1*.

Wattmeter element *a c* measures the load *1–3*; element *b d* measures the load *3–2*; and the combined effect of elements *a c* and *b d* measures the load *2–1*. Thus, the total load on the three-phase circuit is measured by the two elements of the meter that indicate true watts for the whole system.

SYNCHROSCOPES

22. Description.—When two alternators are to be connected in parallel they must first be *synchronized*; that is, the speeds must be adjusted until the frequencies are equal and the electromotive forces are in phase. The alternators are then said to be in *synchronism*; instruments for indicating the phase relation of the machines are called **synchroscopes,** or *synchronizers*. Before the alternators are thrown in parallel synchronism and equality of voltage should be obtained.

23. Fig. 21 shows the interior of a synchroscope of the electrodynamometer type, and Fig. 22 shows the connections of the parts. The two fixed coils *a* and resistor *b* are connected in series across the bus-bars, to which the active alternator is also connected. A movable coil *c* in series with a resistor *d* and a condenser *e* is connected across the terminals of the incoming machine.

The lamp transformer *f* has two primary coils that are excited respectively from the operating machine and the incoming machine and one secondary coil, the circuit of which includes an incandescent lamp.

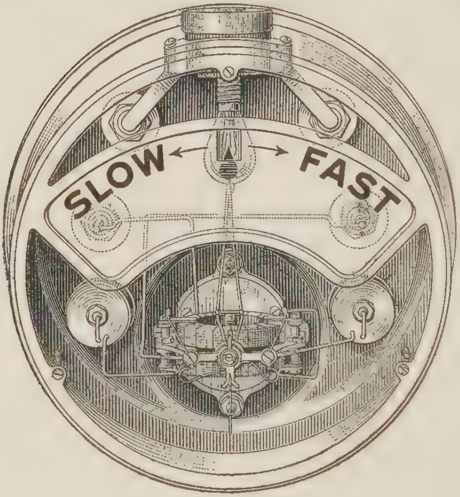

Fig. 21

24. Operation. The inductive reactance and the condensive reactance in the circuits of the operating coils of the instrument, Fig. 22, are such that when the two alternators are in exact phase or in phase opposition, the currents in coils *a* and *c* differ in phase by 90°. Under these conditions, there is no effective torque on the movable coil and its control spring causes it to assume a position in which pointer *g* is vertical.

The phase relation of the magnetizing currents in the coils of the transformer is such that when the two machines are in phase the maximum electromotive force is set up in the secondary coil, and the lamp lights, thus illuminating the scale and the pointer. When the machines are in phase opposition, the electromotive force of the secondary is of minimum value and the lamp is dark. The pointer is behind the glass scale and cannot at this time be seen.

When the frequencies of the machines differ, the phase angle between them changes and a torque is exerted on the movable coil. The pointer swings back and forth over the scale, and at the same time the lamp is lighted intermittently, producing an appearance of rotation of the pointer.

When the pointer is apparently moving toward the side marked *Fast*, Fig. 21, the indication is that the incoming machine is rotating too fast. An apparent rotation toward the side of the scale marked *Slow* indicates that the machine is too slow.

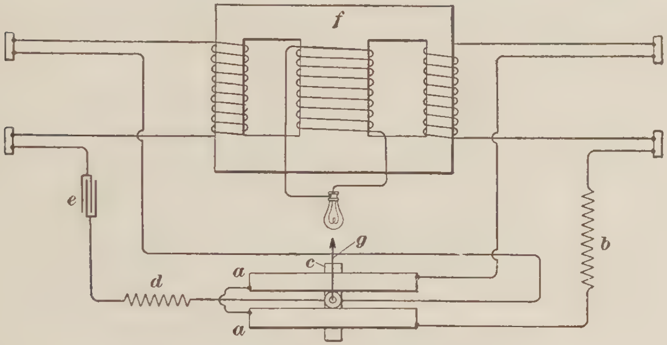

FIG. 22

If the machines have the same frequency but are not in phase, the pointer will come to rest at some point on the slow or fast side of the scale.

Perfect synchronism is indicated when the pointer comes to rest at the central point of the scale at the time when the lamp is of maximum brightness. If the voltages are correct, the machines may then be thrown into parallel connection.

D'ARSONVAL INSTRUMENTS

25. Description.—The **oscillograph** is an instrument that indicates or records the instantaneous values of rapidly varying quantities, such as an alternating voltage or current. It is an extremely sensitive galvanometer, the moving part of which is very light. Several forms are in use; Fig. 23, shows the principle of an oscillograph of the D'Arsonval type.

A light metal strip *a* hangs from supports *b* in the form of a loop between the poles of a permanent magnet. The sides of the loop are kept parallel by bridges *c* and *d*, and a spring *e* attached to a pulley in the bottom of the loop keeps the strips taut. A small mirror *f* is mounted on the strips. The moving system is immersed in an oil bath; a lens in the containing vessel placed near the mirror allows the light rays from some source of light to strike the mirror. The oil serves to dampen the movements of the strip.

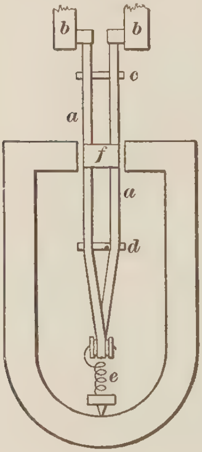

FIG. 23

26. Operation.—Current in the loop, tends to turn it according to the principle of a D'Arsonval galvanometer. The mirror *f* is deflected by this twisting action. If the direction of the current is reversed, the loop is twisted in the other direction. The spring brings the loop to normal position when the current ceases. The movable system is so sensitive that when the current is alternating the loop is twisted first in one direction and then in the other, and the mirror is deflected from side to side in unison with the changes in the current through the strip. The instrument may be used either as an ammeter or as a voltmeter.

The mirror on the loop vibrates on a vertical axis, and a ray from the source of light, if reflected from this mirror to another mirror vibrating on a horizontal axis in synchronism with the current, and thence reflected to a screen, will appear as a curve representing a complete cycle. The horizontal mirror is usually vibrated by means of a small synchronous motor.

For recording purposes, a strip of photographic paper is so mounted on a rotating cylinder as to receive the ray from the mirror on the loop. When the paper is developed, a curve, which may represent several cycles, may be obtained.

Two or more moving elements may be provided, and the change in two quantities, such as voltage and current, can be recorded on the same strip of paper. The phase relation of the quantities may thus be studied.

In Fig. 24, curve *a* represents a voltage curve, and *b*, a lagging current curve as traced on the photographic strip of paper by action of two separate movable elements.

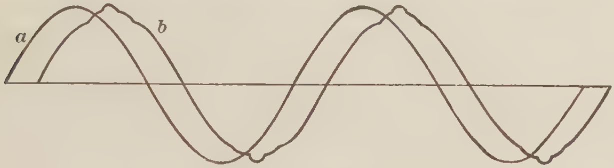

FIG. 24

ELECTROSTATIC INSTRUMENTS

GROUND DETECTORS

27. Description.—The general operating principles of electrostatic instruments for use on either direct-current or alternating-current circuits are explained in *Direct-Current Measuring Instruments*. Instruments of this type are made for the measurement of high voltages and for the purpose of detecting the presence of grounds on line wires. Such instruments require but little current for their operation and may, therefore, be left connected to the circuit at all times with only very small loss of energy.

The connections of a three-phase electrostatic ground detector are indicated in Fig. 25. Stationary segments *a*, *b*, and *c* are connected through resistors with the three line wires, and stationary ring *d* is connected through a resistor with the ground. The three segments and the ring, are in the same plane, and the moving vanes *e*, *f*, and *g* are in another plane just below. The vanes are pivoted at their centers, and each of the vanes is provided with a pointer that is directed toward the center of the instrument when all the lines are free from grounds.

28. Operation.—In case a line is grounded, the segment connected to it and the ring *d* become similarly charged. This alters the balanced static condition formerly existing, the two vanes adjacent to the segment turn to a new balanced position, and the pointers are directed toward this grounded segment. If two lines are grounded, the pointer between the two grounded segments will turn toward the one most completely grounded, and the other two pointers will turn toward their adjacent grounded segments.

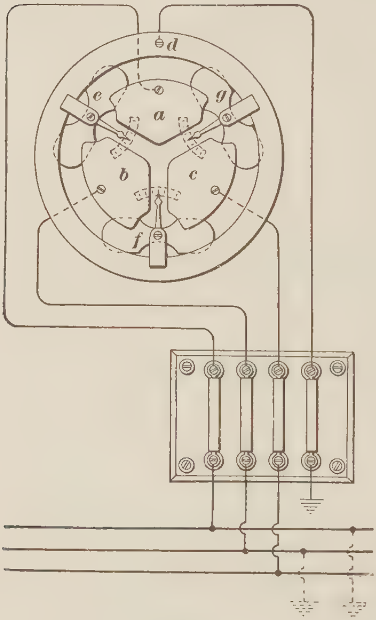

FIG. 25

CALIBRATION OF INSTRUMENTS

29. Alternating-current measuring instruments are often calibrated by comparison with **transfer instruments.** Transfer instruments, usually of the electrodynamometer type, are suitable for use on either direct-current or alternating-current circuits. The transfer instrument is first calibrated on a direct-current circuit and then used in comparison with the alternating-current instrument on an alternating-current circuit so arranged that voltage or current conditions may be adjusted. A comparison of the readings of the two instruments is made, and the accuracy of the alternating-current instrument is checked.

Suitable shunts, multipliers, current transformers, and potential transformers, the characteristics of which are known, should be used as required for the transfer instrument when the tests are made on high-tension circuits.

MEASUREMENTS ON ALTERNATING-CURRENT CIRCUITS

USE OF AMMETERS AND VOLTMETERS

30. Connections of Instruments.—Alternating-current ammeters and voltmeters may be used on low-tension alternating-current circuits in practically the same manner as corresponding instruments are used on direct-current circuits.

In case of high voltage, the voltmeter is connected to the secondary terminals of a potential transformer, the primary of which is connected across the high-tension lines.

In case of a large current, or when the current in a high-tension circuit is to be measured, the ammeter is connected to the secondary of a current transformer the primary of which is connected in series with one of the line wires of the circuit.

31. Power on Circuits of Unity Power Factor.—If the power factor of an alternating-current system is unity, the power is equal to the product of the line current, as determined by an ammeter reading, and the line voltage, as determined by a voltmeter reading, for a single-phase circuit; twice the product for a balanced two-phase circuit; and 1.732 times the product for a balanced three-phase circuit.

With the power factor less than unity, the results found by the foregoing processes must be multiplied in each case by the *power factor*, which is the cosine of the angle of phase difference between the voltage and the current.

Wattmeters are usually employed when power measurements are desired. The connections of indicating wattmeters to polyphase systems are in general similar to those of watt-hour meters, and these are explained in *Watt-Hour Meters*.

32. Impedance—The impedance of a circuit or a coil is equal to the quotient obtained by dividing the reading of a voltmeter connected across the terminals of the coil by the reading of an ammeter connected in series with the coil. In Fig. 26 an alternator is shown at a; an adjustable resistance, at b; the coil under test, at c; the voltmeter, at d; and the ammeter, at e. The impedance of the coil is found by the formula

$$Z = \frac{U_s}{I_s},$$

in which Z = impedance;
U_s = drop of potential across coil c;
I_s = current through coil c.

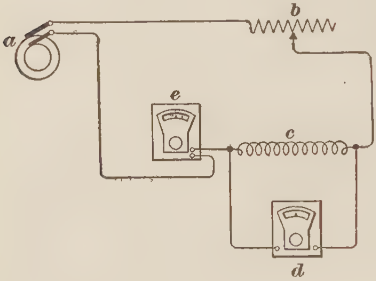

FIG. 26

33. Inductance.—The connections of a voltmeter and an ammeter for testing the inductance of a coil are the same as for the impedance test. The inductance of coil c, Fig. 26, in henrys, is found by the formula

$$L = \frac{\sqrt{U_s^2 - I^2 R^2}}{2\,\pi f I},$$

in which L = inductance;
U_s = reading of the voltmeter, in volts;
I = reading of the ammeter, in amperes;
f = frequency of alternating current;
R = ohmic resistance of the coil.

The ohmic resistance of the coil may be determined by a voltmeter and ammeter test on a direct-current circuit or by a Wheatstone bridge.

In the case of an inductance test on two long line wires without load connection, the line wires should be short-circuited at the distant end and the voltage adjusted to allow about full-load current in the circuit.

EXAMPLE.—When testing the inductance of a coil having an ohmic resistance of 20 ohms, the voltmeter reading was 25 volts when the ammeter reading was 1 ampere, the frequency being 60 cycles per second. What was the inductance of the coil expressed in millihenrys?

Solution.—In this case, $U_s = 25$ volts, $I = 1$ amp., $R = 20$ ohms, and $f = 60$ cycles per sec. By substituting these values and the value of π in the formula, it is found that the inductance

$$L = \frac{\sqrt{25^2 - (1^2 \times 20^2)}}{2 \times 3.1416 \times 60 \times 1} = .03979 \text{ henry, or } 39.79 \text{ millihenrys. Ans.}$$

34. Capacity.—The capacity of any pair of conductors of a cable can be determined by means of a test with a voltmeter and an ammeter. In Fig. 27 an alternator is shown at *a*; a high-tension transformer, at *b*; a current transformer, at *c*; an ammeter, at *d*; a potential transformer, at *e*; a voltmeter, at *f*; and the cable under test, at *g*.

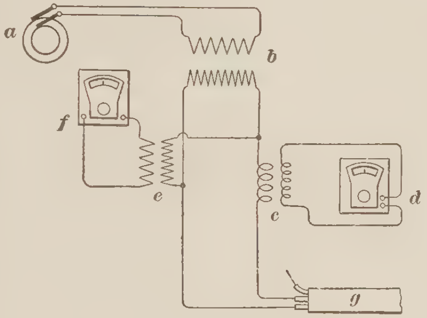

Fig. 27

The ends of two of the conductors of the cable are connected to the secondary circuit of the transformer *b* and there are no connections between these conductors throughout the length of the cable.

If the resistance and the inductive reactance of the circuit is small, the capacity of the pair of conductors, in microfarads, is

$$C = \frac{I \times 10^6}{2\,\pi\,f\,U_c},$$

in which C = capacity;

I = reading of the ammeter, in amperes, multiplied by the ratio of the current transformer;

U_c = reading of the voltmeter, in volts, multiplied by the ratio of the potential transformer;

f = frequency of the alternating current.

The ammeter and the voltmeter should be read as nearly simultaneously as possible.

Example.—A test to determine the capacity of a pair of the conductors of a paper-insulated lead-covered cable 5 miles long was made, the frequency of the alternating current being 60 cycles per second. The reading of the voltmeter was 110 volts, and the ratio of the potential transformer was 100 to 1. The reading of the ammeter was .732 ampere, and the ratio of the current transformer was 5 to 1. What was the capacity of the pair of conductors of the cable?

Solution.—In this case, the voltage U_c impressed on the cable $= 110 \times 100 = 11{,}000$, the current $I = .732 \times 5 = 3.66$ amp., and the frequency $= 60$ cycles per sec. By substituting these values and the value of π in the formula, it is found that the capacity

$$C = \frac{3.66 \times 10^6}{2 \times 3.1416 \times 60 \times 11{,}000} = .883 \text{ microfarad. Ans.}$$

35. Power Factor.—The power factor of an alternating-current circuit can be determined by means of a voltmeter *a*, Fig. 28; an ammeter *b*; and a wattmeter *c*. The product of the voltmeter reading and the ammeter reading equals the apparent watts, or volt amperes. The reading of the wattmeter is the true watts. The $\frac{\text{true watt}}{\text{apparent watts}} =$ the cosine of the angle of lag of the current = the power factor.

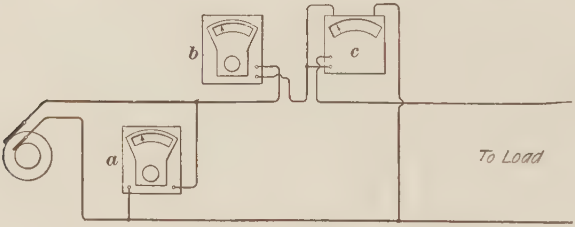

Fig. 28

Example.—When determining the power factor of a circuit, the voltmeter read 110 volts; the ammeter, 50 amperes; and the wattmeter, 4,950 watts. What was the power factor of the circuit?

Solution.—The apparent watts are $110 \times 50 = 5{,}500$, the true watts are 4,950, and the power factor is

$$\frac{4{,}950}{5{,}500} = .9, \text{ or 90 per cent. Ans.}$$

WATT-HOUR METERS

TYPES OF ELECTRICAL ENERGY MEASURING INSTRUMENTS

PRELIMINARY REMARKS

1. The measurement of electricity distributed for commercial purposes is based on the following units: The *ampere*, the unit of current; the *volt*, the unit of electromotive force; and the *watt*, the unit of electrical power. From the first and the third of these units are derived the *ampere-hour* and the *watt-hour*, which mean, respectively, an ampere of current or a watt of power maintained for 1 hour. As these latter units combine the elements of both rate and time, they are adapted to the measurement of the supply of electricity, that is, electrical work, or energy. The watt-hour is the more useful of the two units, because it is a direct measure of electrical work, and its multiple, the *kilowatt-hour* (1,000 watt-hours), is the unit generally employed for commercial purposes.

2. *Ampere-hour meters* and *watt-hour meters* derive their names from the units in which they register. An ampere-hour meter integrates, or adds together, products of current and time without regard to the voltage at which the current is supplied. Consequently, an ampere-hour meter is useful only when it is desired to know merely quantity of electricity, as in storage-battery charging or in electroplating, or when the meter is used on a constant potential circuit, so that the amount of energy supplied can be computed by multiplying the

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ampere-hours registered by the potential of the circuit in volts, which will give the energy in watt-hours. In commercial practice, fluctuations in line voltage cause inaccuracies in the computation of energy from the readings of ampere-hour meters, but on circuits with well-regulated voltage, the inaccuracies will be slight, and these meters are used to some extent in this way, although the general practice in the United States is to use watt-hour meters.

3. The measurement of electricity is accomplished through the different effects it produces. The *chemical effects*, such as the decomposition of an electrolyte, are utilized in some ampere-hour meters; the *magnetic effects* are the basis of all the motor types of meters, now in general use; and the *heating effects* are the basis of all hot-wire types of instruments.

CHEMICAL METERS

4. The **Edison chemical meter** is the earliest type of commercial direct-current meter. Its design is based on the chemical law that 1 ampere-hour of electricity passing between zinc plates immersed in a solution of a salt of that metal transfers from one plate to the other 1,224 milligrams of zinc. The meter is constructed on the shunt principle, and only .001 part or less of the main current is passed through the measuring cell, which consists of two zinc plates in a solution of zinc sulphate. The ampere-hours of electricity that pass through the meter are computed from the loss in weight of the positive plate. This meter, though used quite extensively at one time, is now practically obsolete.

5. The **Bastian electrolytic meter** depends on the principle that the amount of water decomposed by the passage of electricity is directly proportional to the electric current. The meter consists of a glass tube containing water in which are immersed electrodes of proper size. As the water is decomposed into colorless gases by the passage of electricity through it, its level will be lowered and the amount of electricity in ampere-hours can be read from a suitably calibrated scale. For a fixed voltage, the scale may be calibrated in watt-hours or in kilowatt-hours. A film of oil on the water protects it from evaporation, and the addition of a small quantity of caustic soda prevents freezing. The meter is for direct current only and is made only in small capacities; its use is therefore limited.

MOTOR TYPES OF METERS

CLASSIFICATION

6. Motor type meters include both watt-hour and ampere-hour meters. There are in all motor type meters, three essential elements: (1) a motor causing rotation, (2) a means for providing the necessary load, or drag, and (3) a registering mechanism that will integrate, or sum up, the instantaneous values of the electrical energy passing. Watt-hour meters may be classified, according to the kind of motor used, into the *commutator type*, *mercury type*, and *induction type*.

COMMUTATOR TYPE METERS

7. General Principle.—As shown in Fig. 1, the **commutator type watt-hour meter** usually has connected in the circuit to be measured two open-wound field, or current, coils *b*. Between them rotates an armature *a*, the windings of which are connected across the circuit. In series with the armature is placed a high resistance *r*, so that the current in the armature is very small. As the armature revolves

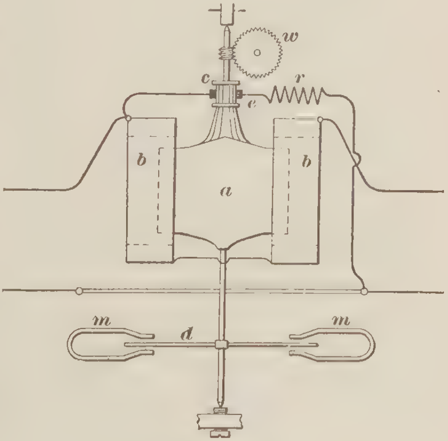
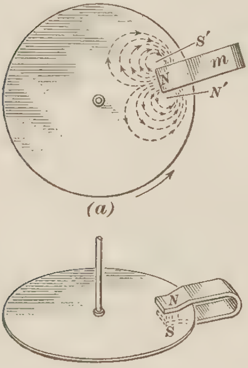


FIG. 1

at a slow speed, practically no counter-electromotive force is generated, and its current depends on only the potential of the circuit. As the armature circuit is permanently closed when the meter is in service, the armature current is continuous. The current in the field coils, however, depends on the use of energy in the circuit on which the meter is connected. Current in the field coils causes magnetic flux, and the reaction between this flux and the current in the armature conductors causes the armature to rotate. The commutator *c*, against which bear the stationary brushes *e*, connects the coils successively in circuit as they come into active positions.

8. The torque exerted on the moving element of the watt-hour meter is proportional to the product of the values of the currents in its field coils and armature. The field coils carry the main current, or a fixed part of it, and the current in the armature is proportional to the voltage of the main current; consequently, the torque of the watt-hour meter is proportional to the rate at which energy is expended in the circuit. To make the speed of the meter proportional to the torque, there must be provided a load that will vary directly as the speed. This is accomplished by a generator consisting of a disk *d*, Fig. 1, of copper or aluminum, mounted on the axis of the armature and revolving between the jaws of permanent magnets *m*. The disk forms a closed conductor of practically constant resistance, in which are generated eddy currents directly proportional to the number of magnetic lines of force cut in a given time or to the speed of the meter.



(*a*)

(*b*)

FIG. 2

9. The relative directions of the eddy currents with respect to the poles of one of the permanent magnets are as indicated in Fig. 2 (*a*), which shows a top view of the disk assumed to be rotating counter-clockwise between the pole pieces of magnet *m*. The polarity of the magnet *m* is indicated by the letters N and S, Fig. 2 (*b*). The eddy currents produce a flux with the polarity indicated by the letters N' and S', Fig. 2 (*a*), the resulting attractions and repulsions opposing the motion of the disk. As the opposing flux is proportional to the eddy currents, it is proportional also to the speed of the disk; hence, the drag of the generator element of the meter on the motor element is directly proportional to the speed.

10. The revolutions of the moving element of the watt-hour meter are recorded by a suitable registering mechanism geared to the shaft. Part of this mechanism is represented in Fig. 1 by a gear-wheel w driven by a worm on the shaft of the moving element of the meter.

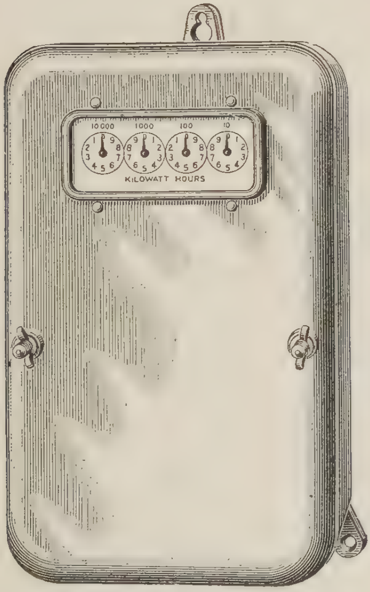


FIG. 3

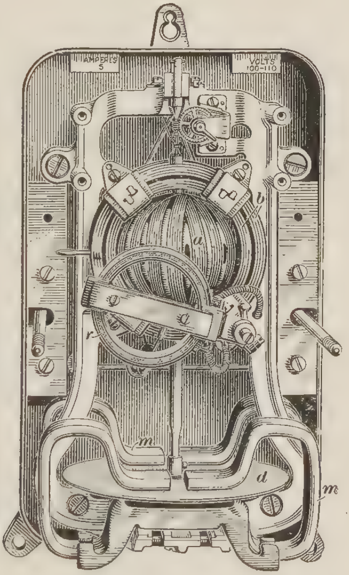


FIG. 4

11. Example of Commutator Meter.—An example of the commutator type of watt-hour meter is the **Thomson watt-hour meter, type C-6.** This instrument with its cover and dial in place is shown in Fig. 3, and with its cover and dial omitted, so as to display the operating mechanism, in Fig. 4. This meter has a spherical armature *a* revolving within circular field coils *b*. The commutator is made up of silver bars assembled about the upper end of the shaft, but insulated from it and from each other. The brushes, each made of two small silver wires, are held against the commutator by the attraction of gravity on weights that are on pivoted arms at right angles to the brushes. In Fig. 4 these weights are concealed by the upper part of the frame of the instrument. Shunt coil *r*, of fine wire, is connected in series with the armature and can be adjusted to such a distance from the armature as to give a flux just sufficient to counteract the strength of the earth's flux, and nearly to overcome the friction of rest, so that the meter will be accurate on light loads.

An aluminum disk *d* revolving between two pair of magnets *m* constitutes the generator element. The main speed adjustment is obtained by shifting the magnets out or in, so as to exert more or less drag on the disk.

The meter registers through a suitable train of gears on a series of four dials reading in kilowatt-hours. Although the meter will register accurately on alternating current, with the exception of a slight error on low power factors, it is used principally as a direct-current meter, because meters of simpler construction are available for alternating current.

MERCURY TYPE METERS

12. General Principle.—For their operation, **mercury motor meters** depend on the principle that a metallic disk will rotate when current is passed between its axis and periphery if the path of the current across the disk is through a magnetic field. The disk in these meters is immersed in mercury, and the current is conducted to and away from it by the mercury. The flux acting on the disk may be produced either by a permanent magnet or by an electromagnet energized by a potential circuit. The retarding, or generator, element is practically the same as that used in commutator type meters. In some meters, the drag magnets act directly on the disk constituting the motor element, and in others, on a separate disk.

13. The construction of the mercury type watt-hour meter is shown diagrammatically in Fig. 5. A thin copper disk *d* completely immersed in mercury in a chamber of molded insulating material constitutes the armature, which is in electrical contact with terminals *c* embedded in the insulating material on each side. In the upper molded insulation piece, forming the mercury chamber, is embedded a steel plate, or ring, *e*, which acts as a return for the lines of force from a potential-circuit magnet. This magnet is below the chamber and is excited by a potential coil *f*, in series with which is a non-inductive resistance *g*; the centers of the pole pieces *p* are in the same diametric line as the contacts of the mercury chamber.

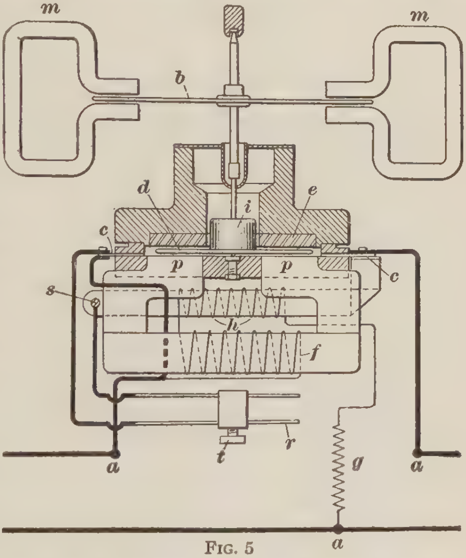


FIG. 5

The line current, or a part of it, between the contacts *c* is therefore subject to the influence of the flux through the disk between the poles and the plate *e*, and this flux is proportional to the line voltage. A continuous torque proportional to the power is thus obtained. Some retarding effect is caused by the eddy currents set up in the armature disk, but the main retarding effect is obtained by a separate disk *b* rotating between permanent magnets *m*. The main retarding effect is relatively large compared with that of the armature disk, so that error on varying voltage is largely eliminated and the speed of the disk is made proportional to the power.

14. The light-load adjustment is obtained with a thermocouple compensating device *s* consisting of two strips of dissimilar metal joined together and surrounded by a heating coil *h* of resistance wire in series with the potential magnet coils. The purpose of the thermocouple is to pass a low-potential current through the armature in order to give the slight torque necessary to overcome bearing friction. To obtain a proper compensating value, the current from the thermocouple may be varied by means of two resistance wires *r* and a thumbscrew clamp *t*. Changing the position of the clamp changes the resistance in the thermocouple circuit only. The thermocouple is so arranged that the current set up by it has the same direction through the armature chamber no matter which way the load current passes; therefore, some meters having thermocouples must be so connected that the direction of the load current through the armature agrees with that of the thermocouple, though in some types the thermocouple connections can be reversed.

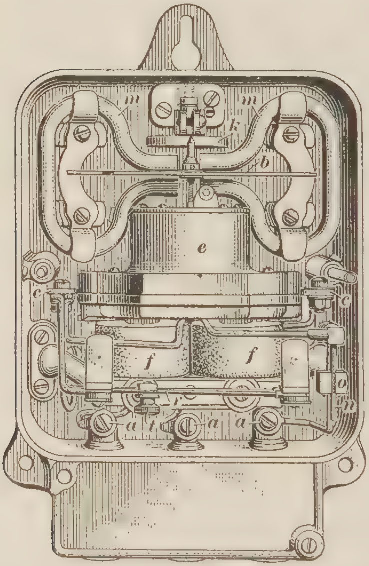


FIG. 6

The thermocouple is omitted from some 110-volt meters of this type, and light-load compensation is obtained by passing some of the potential-coil current through the armature disk, thus giving an initial, or starting, torque that may be regulated by an adjustable resistance in the potential-coil circuit.

In some meters, the adjustable resistance in the potential-coil circuit is used in addition to a thermocouple, the resistance of the thermocouple circuit being in that case non-adjustable.

15. Meters of the type shown in Fig. 5 have no lower bearing. A hardwood float *i* attached to the armature is so proportioned as to give buoyancy, or "lift," to the entire moving system when armature and float are immersed in the mercury. The lower end of the shaft is within a ring that serves as a guide bearing.

16. Examples of Mercury Type Meters.—A view of the interior of one of the **type D Sangamo watt-hour meters** is shown in Fig. 6. The armature disk and the hardwood float are within the chamber *e*, which contains the mercury. A copper contact *c* enters the chamber at each of the places indicated. The potential coils are shown at *f*, one on each leg of the frame of the potential magnet. A retarding action is obtained by mounting a disk *b* so as to rotate between the pole pieces of permanent magnets *m*. One of the two resistance wires, which, in connection with thumbscrew clamp *t*, are used to regulate the current through the potential coil, is shown at *r*. The thermocouple is not used in this instrument. The resistance *g*, Fig. 5, also is concealed in Fig. 6. On comparing Figs. 5 and 6, it will be observed that the outside of the chamber is shown in Fig. 6 and that Fig. 5 is a sectional view. It will be seen, in addition, that the potential coils are shown on the yoke of the magnet frame in Fig. 5, and on the legs in Fig. 6. Connecting wires may be brought through holes in the bottom of the case to the meter terminals *a*, Figs. 5 and 6.

17. Sangamo watt-hour meters for capacities exceeding 10 amperes, direct current, are used with ammeter shunts and are adjusted for use with the shunts by means of a heavy resistance wire *n*, Fig. 6, connected, through clamp *o*, in series with the armature. By moving the clamp, the voltage drop through the armature circuit may be adjusted to the correct value for the shunt. The shunt is of such a relative resistance that 10 amperes will pass through the meter at full load. A proper ratio is used in the recording train, corresponding with the ratio between the total current and that shunted through the meter, so that the dials read correctly in kilowatt-hours.

18. In the type of instrument shown in Fig. 6 the main speed adjustment is made, not by shifting the drag magnets *m* with respect to the disk *b*, but by shunting more or less of the flux between the upper poles of the two drag magnets by means of a small soft-iron disk *k*. The lower the position of this disk, the less will be the drag of magnets *m* and the higher will be the speed of the meter for a given driving torque.

19. The **Sangamo direct-current ampere-hour meter** has the same general construction as the watt-hour meter, except that a permanent magnet sets up the magnetic flux through the armature disk, and this flux is therefore constant. The torque is thus proportional to the current passing through the armature. The usual arrangement of the retarding disk and magnets gives a speed proportional to the current instead of to the power. A record is thus obtained of ampere-hours, entirely independent of the voltage of the circuit.

INDUCTION TYPE METERS

20. Induction type meters are adapted for use with alternating current only, and are essentially small alternating-current motors. All of them depend on the same basic principles for their operation, although they differ considerably in details of construction.

21. General Principle of Single-Phase Induction Meter.—The current coils and potential coils in a single-phase induction watt-hour meter are so arranged as to produce a rotating magnetic flux by the split-phase method. In this rotating flux is placed a rotatable closed secondary in the form of an aluminum disk or cup in which the induced currents, reacting against the flux, cause torque. The disk, or cup, revolves near permanent magnets also, and eddy currents proportional to the speed are generated in it, thus furnishing the load necessary to keep the speed proportional to the torque.

The series, or current, windings consist of one or two coils that have comparatively few turns and are practically non-inductive. These coils are mounted on laminated iron cores that project toward the rotor and concentrate the lines of force through it. The potential windings consist of coils wound with a great many turns of fine wire upon iron cores and so designed as to give the current in the potential circuit a lag of about 90° behind the voltage. An exact phase displacement of 90° is obtained by auxiliary windings and closed circuit secondaries used in combination with the potential windings.

The series, or current, coils are connected in series in the circuit to be measured, and the potential coils, in shunt across the circuit. The magnetic effect of the first is proportional to the current in the circuit, and of the second, to the voltage of the circuit, so that the resultant effect at any instant is proportional to the product of these values at that instant, or to the power in the circuit. The series coils, together with their magnetic circuit, are sometimes called the *series element* of the meter; the potential coils and their magnetic circuit, the *shunt element*.

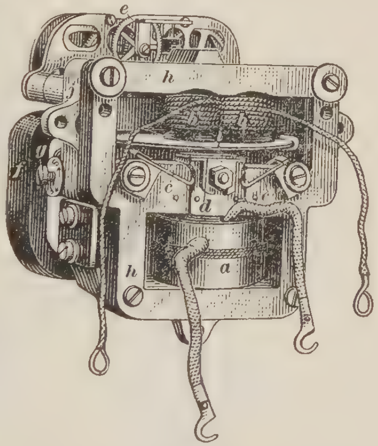


FIG. 7

22. The fundamental principle of the induction type watt-hour meter is practically the same as that of the induction type watt indicator, or indicating wattmeter, which is described in another Section. The essential difference between the two is that the movable element of the watt-hour meter is free to rotate continuously and the rotation of the wattmeter is limited by a control spring.

23. Example of Single-Phase Induction Watt-Hour Meter.—A typical example of the induction type meter is furnished by the **Westinghouse type OA meter.** Fig. 7 shows the rear of a type OA single-phase meter element removed from its case so as to display the arrangement of the coils, and Fig. 8 shows this arrangement diagrammatically; both illustrations should be consulted in reading the description.

All the coils are wound on the laminated iron frame, or core, *h*. The series coils *b* have few turns and are practically non-inductive; the shunt, or potential, coil *a* has a large number of turns of fine wire and is highly inductive. The currents in the coils *b* and *a* set up the shifting, or rotating, flux that causes the rotation of disk *i*. Only part of disk *i* can be seen in Fig. 7; the remainder extends through a slot in the main frame *j* of the meter, so as to come between the pole pieces of two permanent magnets, part of one of which is shown at *f*. These permanent magnets cause the necessary drag on the disk, proportional to the speed. The rotation of the disk operates the registering mechanism *e*, Fig. 7.

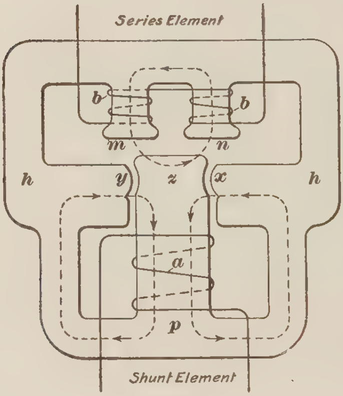


FIG. 8

24. Power-Factor Compensation.—Although the power in non-inductive circuits is the product of the current and the voltage, in circuits in which inductive apparatus, such as motors or arc lamps, are connected, the current lags behind the voltage, and the power in the circuit is the product of the current, the voltage, and the power factor. In order that the meter shall record the true work in a circuit of any power factor, the current in the potential circuit must lag exactly 90° behind the voltage. This phase relation is obtained in the Westinghouse type OA meter by making the potential circuit of high inductance and by placing an adjustable short-circuited secondary *d*, Fig. 7, around the pole *z*, Fig. 8, of the shunt element. By varying the position or resistance of this secondary, the exact 90° phase relation can be obtained.

25. Light-Load Compensation.—Compensation for static, or starting, friction in the type OA Westinghouse watt-hour meter is obtained by closed-circuit secondaries *c*, Fig. 7, so arranged with respect to the flux of the shunt element as to establish a small rotating flux. By turning the screw *g*, the closed secondaries can be moved until this auxiliary rotating flux exerts just enough torque on the disk to overcome the starting friction.

POLYPHASE WATT-HOUR METERS

26. General Principle.—Essentially, a **polyphase watt-hour meter** consists of two single-phase measuring elements mounted with a common shaft so as to drive a single registering mechanism. Each measuring element is practically a single-phase meter. The resultant torque that turns the movable system of a polyphase meter is the resultant of the torques exerted by the two separate meter elements, so that, when properly connected, the meter registers correctly the energy

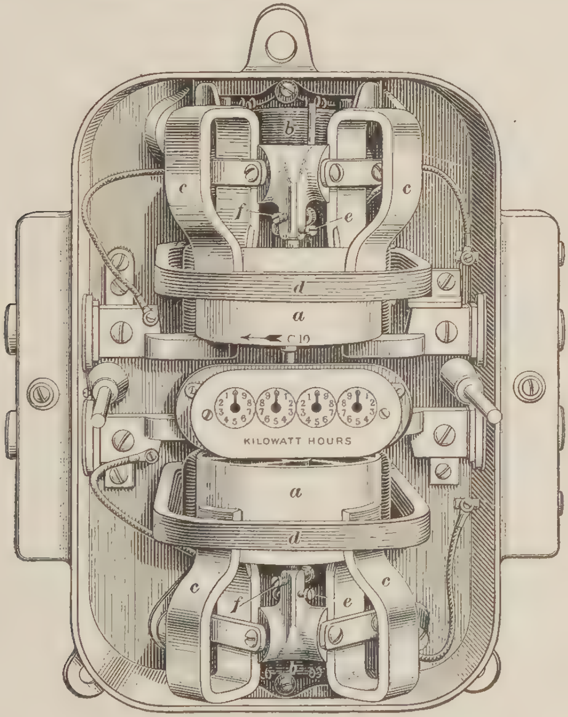


FIG. 9

supplied, or work done, by a polyphase alternating-current system. Most polyphase meters operate on the induction principle.

27. Example of Polyphase Induction Meter.—In Fig. 9 is shown a **Fort Wayne polyphase induction watt-hour meter, type K-3.** The two single-phase elements are arranged symmetrically, one above the register and the other below. The rotating, or secondary, member of each element is an aluminum cup *a*, instead of a disk. The rotating fluxes that drive the cups are set up by potential coils and current coils in the usual manner, each single-phase element having one potential coil and two current coils. The potential coils are within the cups; the current coils are outside, but behind, the cups, where they are not entirely visible in the illustration. In series with each potential coil is an impedance coil *b* that introduces a high inductance into the potential circuit. Retarding effects on the cups are produced by the actions of permanent magnets *c*. The laminated cores *d* are magnetic shields that increase the efficiency of the instrument.

Full-load speed adjustment in this type of meter is made by raising or lowering the permanent magnets. Moving the magnets in toward the dial tends to decrease the speed, under given conditions.

Light-load adjustment is effected by turning screws *e* and *f*. The speed of the meter can be increased on light loads by loosening screw *e* and tightening screw *f*, and decreased by tightening screw *e* and loosening screw *f*. Movement of either pair of screws alters the position of a small coil (not visible in Fig. 9) on a steel member in the core of the potential coil. In series with the small coil is an adjustable resistance for lagging the meter on high frequencies. The coil and the resistance shunt a small part of the impedance coil, so as to give a flux nearly in phase with the electromotive force. Another small coil on the potential magnet core has in series with it an adjustable resistance for lagging the meter on standard frequency.

WATT-HOUR METER CONNECTIONS

PRELIMINARY REMARKS

28. Electrical energy for commercial purposes is distributed either in the form of direct current or in the form of single-phase or polyphase alternating current. The diagrams shown in Fig. 10 to Fig. 21, inclusive, serve to show the principles of watt-hour meter connections for each of the systems of distribution. The diagrams are lettered uniformly, *a* indicating the potential-coil circuit and *b* the current-coil circuit, unless otherwise stated; also, the generator, or source of energy, is assumed to be to the left of the meter and the consuming devices, or load, to the right.

29. For measuring the energy delivered in alternating-current circuits carrying large currents or operating at high voltages, meter, or instrument, transformers are used to reduce in a fixed ratio the values of the voltage and the current applied to the meter, so as to bring them within the range of a meter of ordinary construction. Current and voltage transformers should be used on all high-voltage circuits for purposes of insulation and safety also, even when the value of the current does not require their use.

In the operation of watt-hour meters with current transformers, two sources of error arise: (1) the rate of change of the ratio of transformation for a given transformer increases with a decrease in primary current; (2) the secondary current is not exactly in opposition to the primary current, the phase difference usually increasing as the load decreases. In transformers of proper design, however, these errors are inappreciable except in measurements requiring a high degree of accuracy.

Before an instrument is removed from the secondary circuit of a current transformer, the secondary terminals of the transformer should be short-circuited.

DIRECT-CURRENT AND SINGLE-PHASE ALTERNATING-CURRENT SYSTEMS

TWO-WIRE CIRCUITS

30. To measure the energy distributed in a two-wire direct or alternating-current circuit, a watt-hour meter should be installed with its current coils connected in the ungrounded side of the circuit and its potential coil connected across the circuit, as shown in Fig. 10. If the meter has two separate current coils, both sides of the circuit may be passed through them, as shown in Fig. 11, provided neither side is grounded on the load side of the meter. A ground on the load side of the meter, provided the service, or source, is also grounded, will operate as a shunt, as indicated in Fig. 11, and conduct part of the current around the meter, causing it to record less than the energy delivered; consequently, with a grounded system, the current coils should preferably be connected in the ungrounded line, even though both lines on the load side of the meter are ungrounded, as a fault might develop later, and thus shunt the meter.

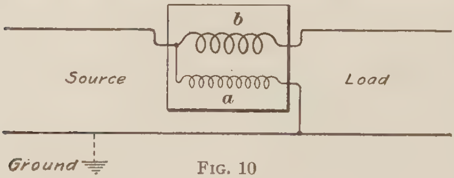


Fig. 10

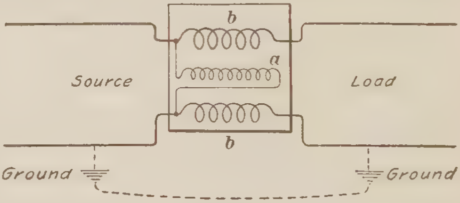


Fig. 11

THREE-WIRE CIRCUITS

31. A three-wire circuit should be considered as two two-wire circuits with one wire in common. The energy in the circuit is the sum of the energy in the two sides, and may be measured by taking the sum of the readings of two watt-hour meters, connected as shown in Fig. 12, or by one three-wire meter, connected as in Fig. 13. As the voltages of the two sides of a three-wire circuit are usually equal, or nearly so, the energy is ordinarily measured by a three-wire meter, in which both sides of the circuit are passed through current coils acting on a single moving element. The potential circuit may be connected from one outside wire to neutral or between the two outside wires, according to the construction of the meter. If the potential circuit is connected to the neutral, the accuracy of the meter depends on the voltages of the two sides of the circuit being balanced. If the potential circuit is connected between the outside wires, the method is accurate only when either the voltages or the currents in the two sides of the system are balanced. In Fig. 13, the dotted line indicates how the potential circuit may be connected between the two outside wires, and the full lines from the same point indicate how the potential circuit may be connected between the neutral and one outside wire.

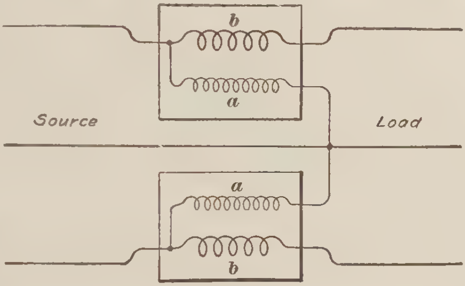


FIG. 12

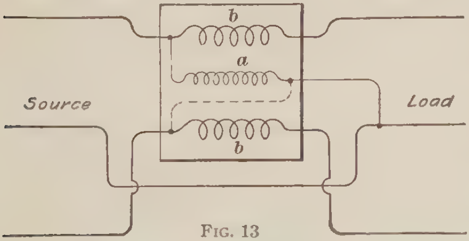


FIG. 13

On direct-current two-wire or three-wire circuits carrying large currents, the current coils of watt-hour meters are usually connected in parallel with low-resistance shunts, so that the meters receive only a relatively small, but definite, proportion of the main current.

POLYPHASE SYSTEMS

TWO-PHASE SYSTEMS

32. The usual forms of two-phase circuits are: (1) the two-phase, four-wire circuit, in which the two phases are entirely separate; (2) the two-phase, three-wire circuit, in which the two phases have a common return wire; and (3) the two-phase, four-wire circuit, in which the two phases are interconnected at the middle points of the phase windings.

33. The energy expended in a two-phase circuit can be measured by two single-phase watt-hour meters, one connected on each phase, or by a polyphase, or two-element, watt-hour meter having one of its elements connected in each phase. In a two-phase, three-wire circuit, the current in the common wire is equal to the vector sum of the currents in the other two wires. If the system is balanced, the relative values of voltages between the different conductors and of current in the conductors are as shown in Fig. 14, which shows also the method of connecting a two-phase watt-hour meter on a three-wire two-phase system. The letters E and I stand for voltage and current, respectively.

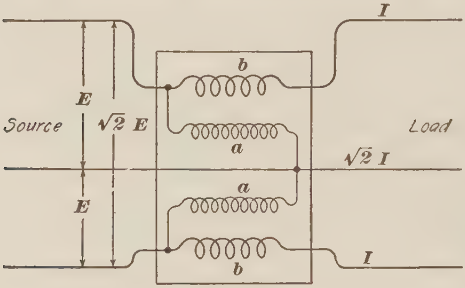


Fig. 14

If the phases of a two-phase circuit were perfectly balanced, the energy delivered in each phase would be the same, so that twice the reading of a single-phase watt-hour meter connected in one phase would give the total energy; but, in commercial practice, this condition cannot be maintained, so that either the two-meter method or the polyphase-meter method should always be used.

THREE-PHASE SYSTEMS

34. In practice, three-phase circuits usually have three wires especially for power transmission and for carrying motor load; if the load consists of both motors and lights, a fourth, or neutral, wire is used, one terminal of each lamp being connected with the neutral and the other with one of the three main wires. Three-phase circuits may be combined by means of either star or delta connections, at either the generating or the receiving end, as explained in another Section.

The voltage of a three-wire three-phase circuit is considered as that between any two of the three main wires. The total energy delivered through a three-phase system is equal to the sum of the energies delivered through the various phases. In a balanced three-phase system, each phase delivers the same amount of energy as either of the other two, and the total energy is the energy per phase multiplied by 3. Several methods are available for measuring the energy in a three-phase circuit: the *three-meter method*, the *two-meter method*, the *one-meter method*, and the *polyphase meter method*.

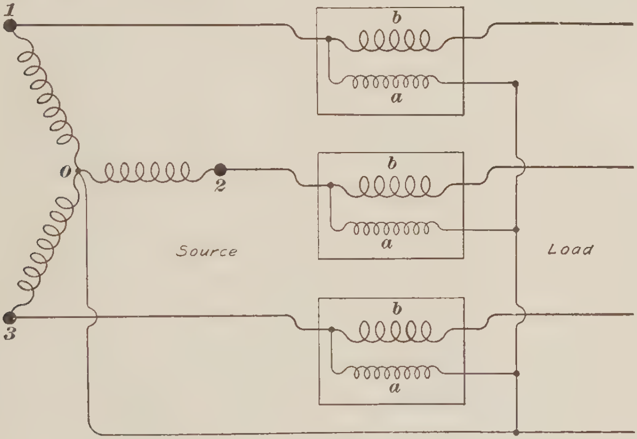


FIG. 15

35. Three-Meter Method.—The energy delivered in a star-connected, three-phase, four-wire circuit can be measured with three single-phase watt-hour meters, the current coil of each being connected in a different phase wire and all the potential circuits connected to the common, or neutral, wire, as shown in Fig. 15. Each meter measures the energy in one phase, and all the meters run forward, or have positive readings. If the system is balanced, each meter measures one-third of the total energy. The numerals *1*, *2*, *3*, Fig. 15, represent the terminals of a star-connected generator with its neutral at *0*.

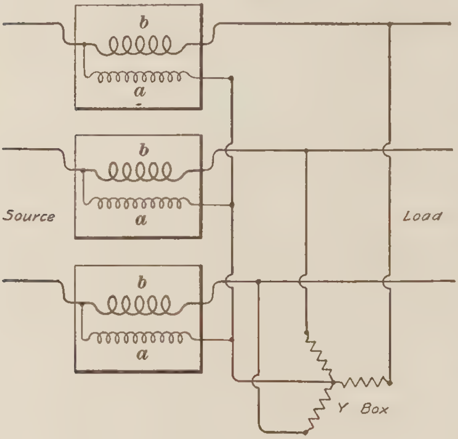


FIG. 16

In a three-phase, three-wire, star-connected circuit with an inaccessible neutral, or in a delta-connected circuit, the foregoing method may be used by the creation of an artificial neutral point. For this purpose, a **Y** box, Fig. 16, is used; this consists of three equal, non-inductive resistances connected together at one end, which becomes a neutral point when the other ends are connected to the phase wires. The three-meter method may always be used for measuring the energy delivered in three-phase, four-wire circuits, and is correct for any conditions of power factor or unbalance.

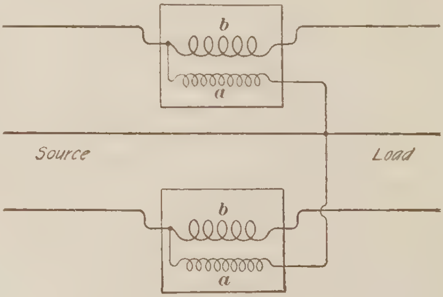


FIG. 17

36. Two-Meter Method.—The energy delivered in a three-phase, three-wire circuit can be measured by means of two watt-hour meters connected as shown in Fig. 17.

The current coils are connected in two of the wires, and the potential coils, between these two wires and the third wire. The algebraic sum of the readings of the two meters gives the energy in the circuit under all conditions of unbalanced load or power factor.

If the power factor of the load is greater than .5, that is, if the angle of current lag is less than 60°, the arithmetical sum of the readings of the two watt-hour meters gives the energy supplied. If the power factor is less than .5, that is, if the angle of current lag is greater than 60°, the torque due to the changed relations of the currents in the current and potential coils in one of the meters causes it to run backwards, or have a negative reading, and the arithmetical difference of the two readings gives the total energy.

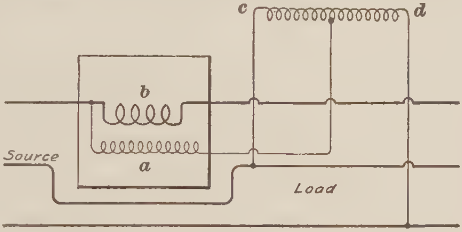


FIG. 18

37. One Single-Phase Meter Method.—The energy delivered in a three-phase, three- or four-wire circuit that is perfectly balanced can be measured with one watt-hour meter with its current coils in one phase wire, and its potential circuit connected to the neutral wire or to a neutral obtained with a Y box. The meter measures the energy in one phase, and, since, in a balanced system, the energies in the three phases are equal, three times the reading of the watt-hour meter gives the total energy.

A single-phase watt-hour meter may also be used on a three-phase, three-wire system by connecting the current coil in one wire of the system and connecting the potential coil between that wire and the middle point of an autotransformer that is connected between the other two wires of the system. This method is illustrated in Fig. 18, in which *c d* represents the autotransformer. In this case, the meter reading must be multiplied by 2 in order to give the total energy delivered by the system.

The one-meter method gives correct results for all power factors, provided the circuit is balanced. Its use should be restricted to measuring energy supplied to synchronous apparatus, which should be carefully tested for balance. On commercial distributing circuits, it is impossible to secure a condition sufficiently balanced to permit of accurate results by the use of this method.

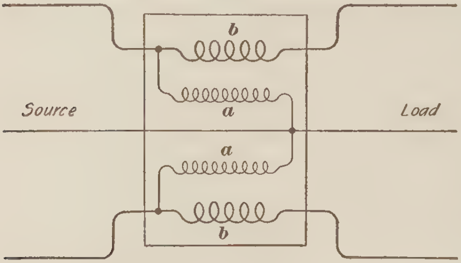


FIG. 19

38. Polyphase Meter on Three-Phase, Three-Wire System.—Polyphase watt-hour meters made for use on three-phase, three-wire circuits are designed in accordance with the two-meter method and integrate the registration of two separate moving elements. On account of convenience, such meters are generally used in commercial practice in place of two single-phase watt-hour meters.

The connections of a polyphase watt-hour meter to a three-phase, three-wire system are illustrated in Fig. 19. The system of connections is the same as that of the two-meter method, as may be seen by comparing Figs. 17 and 19. How-

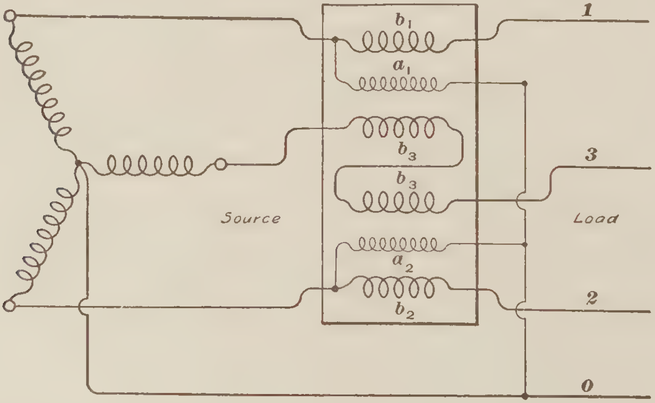


FIG. 20

ever, no modification of the reading of the polyphase meter is necessary, even if the power factor of the system is below .5, because it has only one movable system on which the torque is at all times the resultant of the torques of the two single-phase elements.

39. Polyphase Meter on Three-Phase, Four-Wire System.—Instead of using three single-phase watt-hour meters, one three-phase, four-wire meter may be used to measure the energy in a three-phase, four-wire system, as shown in Fig. 20. This instrument has two potential elements a_1 and a_2 connected from line wires *1* and *2*, respectively, to the neutral *0*. There are four current coils; one in line *1*, one in line *2*, and two in line *3*. Each potential coil is acted on by two current coils; one in the line wire to which the potential coil is connected, and one in the third line wire, to which neither potential coil is connected. As the voltages of the two phases containing the potential coils are displaced 120° from each other and also from that of the third phase, their resultants will

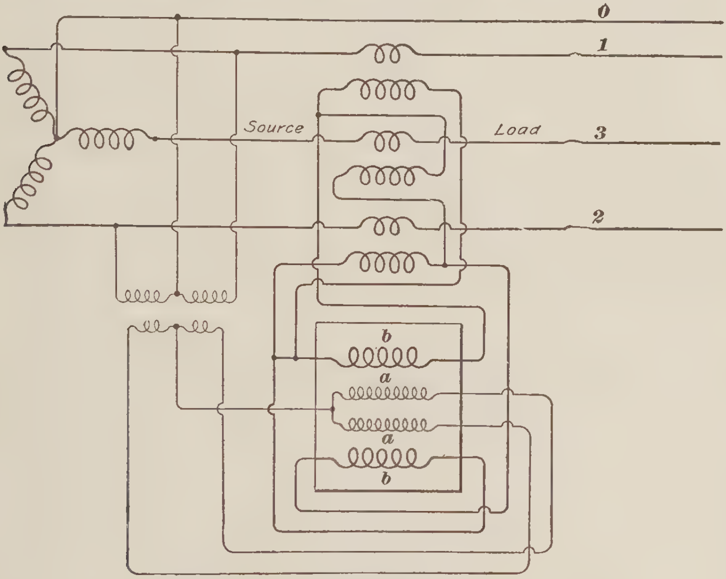


FIG. 21

be equal and opposite to the voltage of the third phase, and, consequently, their combined effect on the two current coils in the third line wire will be the same as the voltage of the third phase would have if it acted directly on one current coil, provided the coils are correctly connected for polarity. Three-phase, four-wire meters are accurate on any power factor, but only on balanced voltages.

40. The same result can be obtained by using a three-phase, three-wire meter that has the two current coils connected in circuit by means of current, or series, transformers and by passing the reversed secondary current of the transformer in the third phase through both current coils, one of which is connected in each of the other two phases. Such an arrangement is shown in Fig. 21, in which instrument transformers are used for both the current-coil circuits and the potential-coil circuits of the watt-hour meter. Current from the secondary of the series transformer in line *3* passes through both current coils of the meter.

TESTING AND MAINTAINING WATT-HOUR METERS

TESTING

CLASSIFICATION OF TESTS

41. Although watt-hour meters are very accurate and reliable instruments, they are subject to mechanical wear and deterioration, and also to electrical disturbances that may affect their accuracy; consequently, they should be systematically tested, both to give them proper care and to furnish absolute assurance of the reliability of their registration. These tests may be classified as: (1) the laboratory or shop test, to ascertain whether the meter is in proper condition before it is installed for use; (2) the installation test, to insure the proper connection of the meter in the circuit, and to make any adjustments necessary for surrounding conditions; (3) the periodic test, made at stated intervals to maintain its accuracy; and (4) the complaint or other special test, made as desired by the consumer or by the central station.

Two general methods of testing watt-hour meters are in vogue: one consists in comparing the power shown by the watt-hour meter with the readings of indicating instruments, and the other in comparing the number of revolutions of the watt-hour meter with the revolutions made in the same time by a rotating standard test meter.

INDICATING-INSTRUMENT METHOD

42. General Principle.—In testing watt-hour meters by means of indicating instruments, a whole number of revolutions of the moving element of the meter under test is timed by means of a stop-watch. At the same time, the power in the circuit is measured by means of indicating instruments. On direct current, an ammeter and a voltmeter should be used; on alternating current, an indicating wattmeter. An indicating wattmeter may be used on direct current, provided reversed readings are taken and the average of these readings is used so as to eliminate the error caused by the earth's or other external magnetic fields. This plan, however, is not practicable unless the load is absolutely steady; consequently, it is better practice to use indicating wattmeters on alternating current only.

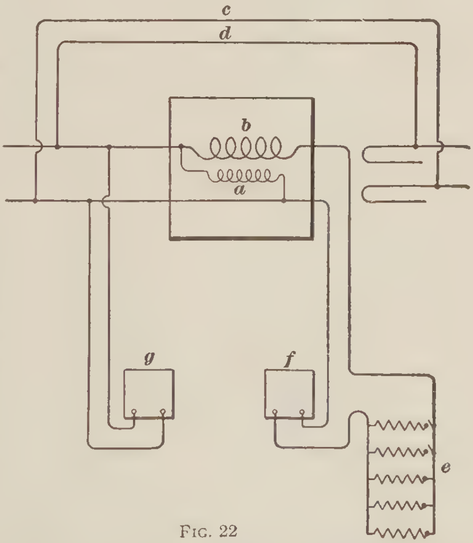


FIG. 22

43. Connections.—The connections for testing a watt-hour meter on a two-wire circuit when both sides of the circuit pass through the meter are shown in Fig. 22. The meter is first shunted by wires *c* and *d*, so as to keep a closed circuit from the service to the consumer's load. Then the consumer's load is disconnected from the meter, and in its place is substituted a temporary, adjustable load *e* consisting of a water rheostat, a lamp bank, or a *load box*, which is a special type of rheostat designed for meter testing. In series with the temporary load is an ammeter *f*. When a voltmeter *g* has been connected across the circuit, the connections are ready for the test.

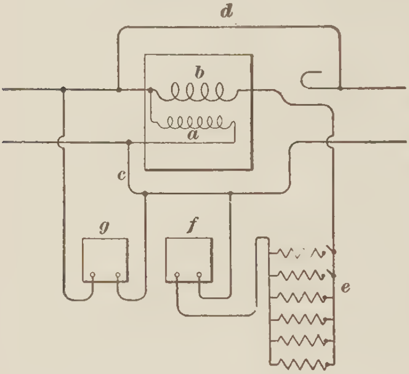


FIG. 23

When a two-wire meter has only three terminals, one line wire *c*, Fig. 23, leads directly to the consumer's load; thus, it is necessary to use only one wire *d* to shunt the meter. The connections shown in Fig. 23 are otherwise the same as those shown in Fig. 22.

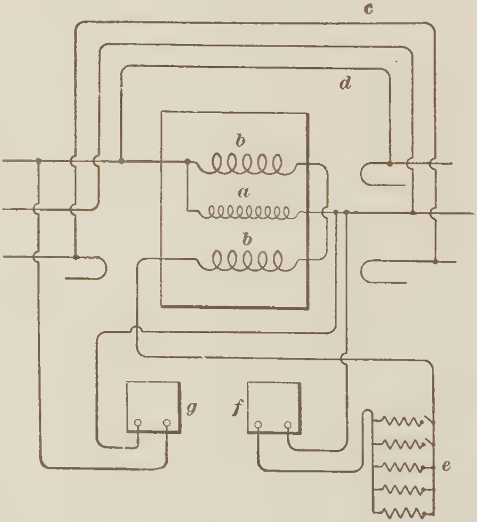


FIG. 24

In order to avoid the use of two ammeters, a three-wire meter can be tested with the two current coils in series on the same load, as shown in Fig. 24, in which *c* and *d* are temporary shunts, *e* is a temporary load, *f* an ammeter, and *g* a voltmeter. The two current coils *b* are in series with each other and with the temporary load and ammeter.

44. Calculations.—The watts indicated by the watt-hour meter are ascertained by the formula

$$P=\frac{K_s R}{S}, \qquad (1)$$

in which P = watts;

K_s = watt-seconds indicated by one revolution of the moving element of the watt-hour meter, and called the *watt-second constant*;

R = number of revolutions observed;

S = observed time, in seconds, for R revolutions.

The constant of the watt-hour meter is always marked on it, usually on the disk or the cup. This constant is usually given in watt-hours; therefore, it must be reduced to watt-seconds by multiplying by 3,600, the number of seconds in an hour. The formula thus becomes

$$P=\frac{3{,}600\, K_H R}{S}, \qquad (2)$$

in which K_H is the *watt-hour constant*, frequently called the *test constant*. In some makes of meters, neither the watt-second nor the watt-hour constant is given, but one applicable to a special formula used with that meter.

After ascertaining the watts indicated by the watt-hour meter, they are compared with the standard watts P_1 obtained from the product of the voltmeter and ammeter readings on direct current, or the readings of an indicating wattmeter on alternating current, to obtain the accuracy of the meter, using the formula

$$\textit{percentage of accuracy}=\frac{\textit{meter watts}\times 100}{\textit{standard watts}}$$

or

$$\textit{percentage}=\frac{P\times 100}{P_1} \qquad (3)$$

Example.—The disk of a 5-ampere, 110-volt Thomson watt-hour meter makes 24 revolutions in 46.6 seconds. The load on the watt-hour meter, as shown by an ammeter and a voltmeter, is 3.3 amperes at 113 volts. The watt-hour constant of the watt-hour meter is .2. What is its accuracy of registration?

Solution.—From formula **2**,

$$P = \frac{3{,}600 \times .2 \times 24}{46.6} = 370.8$$

The load on the watt-hour meter as ascertained by the indicating instruments is $P_1 = 3.3 \times 113 = 372.9$ watts. From formula **3**,

$$\text{percentage} = \frac{370.8 \times 100}{372.9} = 99.4. \quad \text{Ans.}$$

The meter, therefore, was registering 99.4 per cent. of the energy delivered in the circuit at a load of $\frac{372.9}{550}$, or 67.8 per cent., of its rated capacity.

When a three-wire watt-hour meter is tested with the current coils in series, as in Fig. 24, the load has double effect on the meter, making the meter watts about twice the load shown by the indicating instruments. Accordingly, when testing a meter in this way, one-half of the marked test constant is customarily used.

Example.—A 15-ampere, 230-volt, 3-wire Thomson watt-hour meter for a 115-230-volt, 3-wire circuit makes 25 revolutions in 55.3 seconds. The indicating instruments show a load of 9.2 amperes at 113 volts. The current coils of the watt-hour meter are connected in series, and the watt-hour constant marked on the disk is 1.25. What is the accuracy of the watt-hour meter?

Solution.—The values to be substituted in formula **2** are $K_H = \frac{1.25}{2}$; $R = 25$; and $S = 55.3$. Then, the meter watts are

$$P = \frac{3{,}600 \times \frac{1.25}{2} \times 25}{55.3} = 1{,}017.2$$

The indicating instruments show a load of $113 \times 9.2 = 1{,}039.6$ watts. According to formula **3**, the percentage of accuracy is

$$\frac{1{,}017.2 \times 100}{1{,}039.6} = 97.8 \text{ per cent.} \quad \text{Ans.}$$

45. Precautions and Modifications.—The instruments used in meter testing should be compared with standard instruments at frequent intervals to insure the maintenance of their accuracy. For slight errors, a calibration curve should be supplied and proper corrections made to all readings.

In making connections for tests, care must be taken that the watt-hour meter does not measure the potential loss of the indicating instruments, or these instruments that of the watt-hour meter. For example, in Figs. 22 to 24, inclusive, the wattmeter current circuit does not carry the current in the voltmeter; nor does the ammeter carry the current in the watt-hour meter potential circuit. In Fig. 25, the current-coil of neither watt-hour meter carries the current in the potential coil of the other.

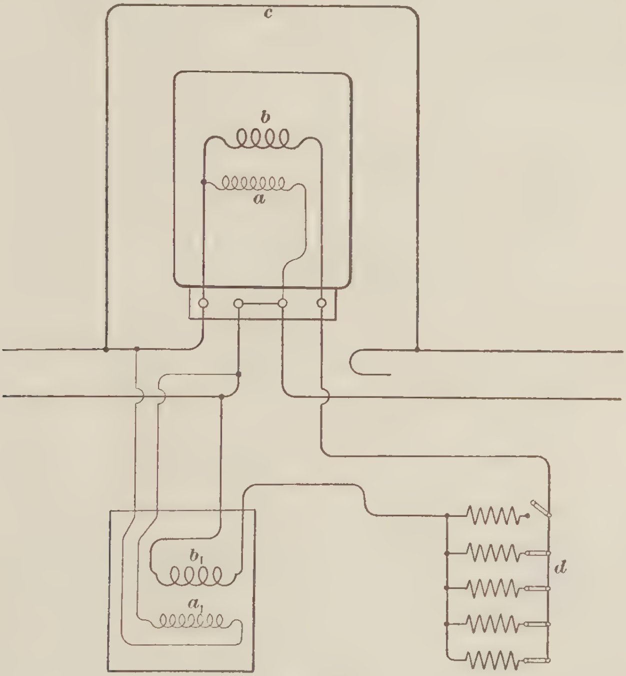


FIG. 25

In place of a voltmeter and ammeter or an indicating wattmeter, a voltmeter and a calibrated resistance may be used. The consumption of power in watts for the different combinations of such a resistance is known for different voltages.

When the calibrated resistance is used for loading the watt-hour meter, the voltmeter readings enable the tester to read the power in watts in the circuit directly from the calibration card for the resistance.

ROTATING STANDARD METHOD

46. General Principle and Calculations.—In the rotating standard method of testing watt-hour meters, the standard is connected in the circuit in series with the watt-hour meter under test and is usually started at the beginning and stopped at the end of a certain number of revolutions of the watt-hour meter. The revolutions made by the standard are read from its register, the observed revolutions of the watt-hour meter compared with it, and the percentage of accuracy obtained by the formula

$$percentage = \frac{K_H R}{K R_s} \times 100,$$

in which K_H = watt-hour constant of meter under test;
K = watt-hour constant of rotating standard;
R = observed revolutions of watt-hour meter under test;
R_s = revolutions of rotating standard, as read from register.

EXAMPLE.—The watt-hour constant of a meter under test is 2, and that of the rotating standard, .25. The standard makes 16.3 revolutions while the meter under test makes 2. What is the percentage of accuracy of the meter?

SOLUTION.—In this test, the value of K_H is 2; of K, .25; of R, 2; and of R_s, 16.3. By substituting these values in the formula, the percentage of accuracy is found to be

$$\frac{2\times 2}{.25\times 16.3}\times 100 = \frac{16\times 100}{16.3} = 98.2. \quad \text{Ans.}$$

47. Connections.—The method of connecting the instruments for the rotating standard method of testing is indicated in Fig. 25. The potential and current-coil circuits of the meter under test are shown at a and b, respectively, and the corresponding circuits of the rotating standard at a_1 and b_1.

The temporary shunt *c* maintains the consumer's circuit. The artificial load is shown at *d*, in series with the current coils of both meters.

GENERAL DIRECTIONS FOR TESTING

48. Artificial Loads.—In general, some form of portable artificial load is used for testing meters on consumer's premises, both to obtain conveniently the load required for the test and to avoid inconvenience to the consumer. Meter-testing rheostats, or load boxes, made of coils of resistance wire, by which the load may be varied in one-half ampere steps, and water rheostats may be used for loading meters from the main circuit on either direct- or alternating-current work. On alternating-current circuits, low-voltage testing transformers also can be used for loading the current coils of the meter with a current of large amperage but low voltage.

49. Calibration Tests.—Meters should be tested on both light and full loads. The light-load test should be made at 5 to 10 per cent. of the rated capacity, usually 10 per cent. on direct-current meters, and 5 or 10 per cent. on alternating-current meters. The full-load test should be made at 50 to 100 per cent. of the rated capacity.

The calibration of a meter should first be made at full load by the magnet adjustment, and afterwards it should be corrected at light load by adjusting the starting coil or the closed secondary coil. If the light-load adjustment is changed materially, the accuracy of the meter at full load should again be checked. All meters should also be examined when the potential circuit is connected but no load is on the fields, to see that the light-load adjustment does not give them any tendency to creep.

50. Testing Meters in Service.—The procedure for testing meters in service should be as follows:

The tester checks the number of the watt-hour meter with that on the test form, or blank, and enters the register reading. He cleans and removes the cover of the meter and connects the test instruments in circuit, usually shunting the consumer's load around the meter, so as not to interfere with his service, and connecting an artificial load, the value of which he can easily control. The test instruments should be set in a safe place, free from vibration and the effects of external magnetic fields.

The tester first examines the meter for creeping, with all load disconnected. He then makes his "as-found" tests on both light and full loads, and records them on the test blank, to show the accuracy with which the meter was recording. He then cleans the meter and examines it thoroughly for defects, removing the jewel and pivot if the meter is at all slow on light load, and replacing them with new ones if they are worn. The tester then recalibrates the meter on full load and then on light load, and after all adjustments are completed, examines it again for creeping. He then disconnects the test instruments and reconnects the consumer's load as originally found. He examines the cover of the watt-hour meter for defects and replaces and seals it, having first set back the register to the original reading before the test, unless the consumer was using the load on which the meter was tested. He then makes a final inspection to see that the meter is running, that all connections are well made, and that the consumer's service is not disturbed.

51. Testing Polyphase Meters.—Polyphase watt-hour meters for two- and three-phase circuits may be tested on single-phase current with the fields in series and both potential elements connected, provided the meter is so designed as to be free from interference effects between the two meter elements, as is the case of those of modern manufacture; or, each element of the watt-hour meter may be tested separately, with both potential circuits connected. If the meter is found to be out of calibration, each element should be tested separately to ascertain whether one element has a greater error than the other. There are available polyphase rotating standards that can be connected in series with the polyphase watt-hour meters on the consumer's load, so that the meters can be tested under the condition of load and power factor on which they are used.

CAUSES OF INACCURACY

52. Primary Causes.—The causes of inaccuracies in watt-hour meters may be classified as (1) those causing them to run too fast, and (2) those causing them to run too slow. A properly designed meter should register within 2 per cent. correct at all points from 5 or 10 per cent. load to 50 per cent. overload. A watt-hour meter, as a rule, should be adjusted to within 1 per cent. correct on both full- and light-load tests.

If a meter runs fast, it may be due to the potential coil or the armature carrying too much current, to the drag magnets not exerting enough retarding effect, or to the presence of stray fields. If a meter runs slow, it may be due to friction from mechanical defects, to too little current in the potential circuit, or armature, or to stray fields.

The effect of mechanical friction is greater on a meter at light loads, because this effect is nearly constant and the torque of the meter is proportional to the load. Friction that will cause a meter to run 10 per cent. slow at 10-per-cent. load will cause it to run only about 5 per cent. slow at 20-per-cent. load, and 1 per cent. slow at full load.

53. Defects in Commutator Meters.—The tester should look for the following defects in inaccurate meters of the commutator type:

1. If fast on both light and full loads: short circuits in the resistance, or starting, coil in series with the armature, or weakened or loose drag magnets.

2. If faster on light load than on full load: loose light-load adjustment, stray fields, vibration, or loose brush tension.

3. If slow on both light and full loads: short or open circuit in the armature, short circuit between commutator bars, short circuit in field, or current, coils, reversed field coil, loose magnets.

4. If slower on light load than on full load: defective bearing or shaft point, rough commutator and brushes, too much brush tension, iron filings on magnets, or other causes of friction on disk or armature, stray fields, or loose or inadequate light-load adjustment.

54. Defects in Induction Meters.—In meters of the induction types, the tester should look for the following:

1. If fast on both light and full loads: short circuit in series reactance of potential coil, or weakened or loose drag magnets.
2. If faster on light load than on full load: loose or defective light-load adjustment, vibration, or short circuit in series coils.
3. If slow on both light and full loads: short circuit in current or potential coils, or loose magnets.
4. If slower on light load than on full load: defective jewel or pivot, friction from dirt or other cause, loose or inadequate light-load adjustment.

MAINTENANCE OF WATT-HOUR METERS

55. Commutators and Brushes.—Commutators and brushes are usually made of silver and, after a short period of use, they become "aged," or tarnished with a coat of silver sulphide. This coating introduces a slight additional resistance in the circuit, but as the condition is permanent, the speed of the meter should be adjusted for it, if necessary, and the tarnish not removed as long as the commutator is smooth. The dirt may be removed from a commutator with a piece of linen tape without removing the tarnish. The loose dirt should be blown out with an air syringe, or brushed out with a camel's-hair brush. If dirt is caked between the segments, it should be removed with a fine wire pick. If the commutator becomes burned or pitted from sparking, it must be smoothed with a piece of worn crocus cloth, and polished.

The brushes should be adjusted so as to lie flat against the commutator, with sufficient tension to prevent vibration and the consequent sparking. The amount of tension necessary on the brush depends considerably on the location of the meter. If it is subject to vibration, the tension of the brushes must be increased to prevent sparking, and the increased friction compensated for with the light-load adjustment.

Open or short circuits in the armature can be detected by testing with a voltmeter or with test lamps the drop in voltage between each pair of adjacent segments of the commutator.

56. Bearings.—The bearing of a watt-hour meter is usually a cupped sapphire or diamond jewel. The shaft is usually equipped with a removable pivot running in the jewel, or it may be terminated in another cupped jewel, a steel ball running between the upper and lower jewels. When a jewel is found to be defective, it should be replaced and the pivot or ball also should be changed.

Diamond jewels are much more durable than sapphire jewels, and when the former are used, the pivot will frequently become flattened, requiring renewal before the jewel. The lower bearings of a watt-hour meter are generally oiled with the best grade of watch oil.

The upper bearing of a watt-hour meter is usually a ring or a guide bearing, into which the top of the shaft fits. It should be kept clean and should be adjusted so as to give proper play to the shaft but not loose enough to allow the shaft to be sprung out.

57. Creeping.—Creeping is a slow rotation of the moving element of a watt-hour meter when there is no load on the circuit in which it is connected. It may be either backwards or forwards, but is usually the latter. All observations for creeping should include a full revolution, as a disk may rotate for part of a revolution after the load is removed, owing to a slight unbalance of the moving element.

The causes of creeping may be incorrect compensation for friction; vibration that reduces the friction of rest; stray magnetic fields; excessive voltage; potential circuit connected on the load side of the meter, so that its current passes through the series coils; or short circuits in the current coils, this applying to induction watt-hour meters only. A leakage or ground in the circuit may be mistaken for a creep; consequently, observations for creep should always be made with the load wires removed from the watt-hour meter.

When creeping of a commutator meter cannot be prevented by properly adjusting the starting coil, a clip is sometimes used. This clip consists of a short, **U**-shaped iron wire, which is fastened on the edge of the disk. The drag magnets will attract the clip and prevent rotation of the disk. The clip must not be so large as to prevent the meter from starting on light load or to rub against the magnets. The clip does not affect the accuracy of the meter, because the retarding effect when leaving a magnet is offset by the accelerating effect on approaching it.

58. Humming.—The humming of an induction watt-hour meter is usually due to a vibration of the shaft in synchronism with the alternations of the current. It may sometimes be stopped by so altering the adjustment of the top bearing as to change the vibrating length of the shaft. Improved top bearings have been devised to overcome this rattling, and old bearings giving trouble can be replaced by new ones of this type. The humming of the meter does not indicate that the meter is registering, as is often supposed, and aside from causing slight additional wear on the bearing, it is objectionable only on account of the noise. Sometimes humming is caused by a vibration of the laminated iron cores or other parts of the meter that have become loose, in which case the meter should be removed from service and sent to the shop for repairs.

59. Registers.—Watt-hour-meter registers should be examined to see that they move freely and engage properly with the moving element of the meter. In the case of new meters and special tests, the *register ratio* should be checked to guard against errors in manufacture. The register ratio can be found by counting the number of teeth in each gear of the register mechanism and dividing the product of the number of teeth on all the driven gears by the number of teeth on all the driving gears. It may also be found by finding how many revolutions of the gear-wheel meshing with the worm or pinion on the shaft are required to cause one revolution of the pointer of the right-hand dial of the register.

READING AND INSTALLING WATT-HOUR METERS

READING WATT-HOUR METERS

60. Definitions.—The energy of the movable element of a watt-hour meter is transmitted through a system, or train, of gears to a series of *hands*, or *pointers*, that rotate over *dials*. A series of dials is imprinted on a *dial face*, and the positions of the hands with respect to the dials indicate the *reading* of the meter. The gears and dials are all part of the register.

In order to simplify the gearing, use is sometimes made of a *register constant*, the number by which the register reading must be multiplied to determine the amount of electrical energy measured by the watt-hour meter. The register constants of meters of recent types are usually either 10 or 100, increasing the capacity of the register to 10 or 100 times its maximum direct reading.

61. Dial Systems and Markings.—The registers of most American-made meters have four dials and record electrical energy in kilowatt-hours, as shown in Fig. 26 to Fig. 29, inclusive. The right-hand dial indicates units, the next tens, the next hundreds, and the next thousands. For this reason, the right-hand dial is sometimes called the *units dial*, the next the *tens dial*, and so on. Each dial is divided into ten divisions, numbered from *1* to *0*. A complete revolution of the units hand carries it over 10 divisions and causes the hand on the tens dial to move one division; a complete revolution of the tens hand carries the hundreds hand over one division, and so on. To distinguish the dials, some manufacturers mark

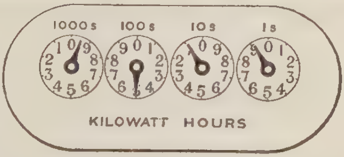


Fig. 26

them *1s*, *10s* (units, tens), and so on, as shown in Fig. 26. In other makes of instruments, as in Fig. 27, the dials are not marked, the position of the dial indicating the value of its readings. In still other types, as in Fig. 28, the value of a complete revolution of the hand is marked above the dial; *10* for one revolution of the units hand, *100* for one revolution of the tens hand, and so on.

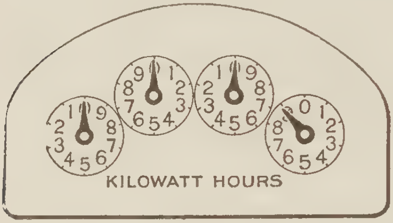


Fig. 27

The highest amount that a direct-reading, four-dial register can record is 9,999; but, as already mentioned, register constants may be employed to increase this amount. When used, the register constant is always fixed by the manufacturer and marked plainly on the dial face, the usual method being to use the words *Multiply by 10*, or *Multiply by 100* (see Fig. 29), as the case may be.

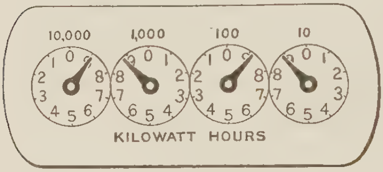


Fig. 28

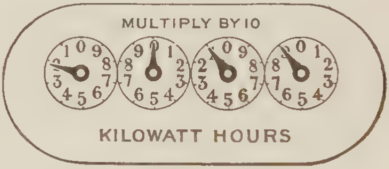


Fig. 29

Registers reading in watt-hours usually have five dials, the lowest dial registering 1,000 watt-hours for one revolution of the hand or 100 watt-hours for each division of the dial. Such a register is shown in Fig. 30, the number above or below a dial indicating the value of one revolution of the corresponding hand.

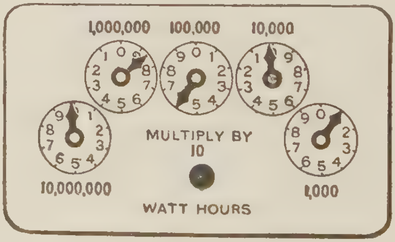


Fig. 30

62. Directions for Reading Watt-Hour Meters.—To record the reading of a watt-hour meter, it is only necessary to write the numbers indicated by the hands from left to right in order. If there is a constant marked on the register, the product of the reading and the constant gives the energy in kilowatt-hours or in watt-hours, depending on the unit for which the register is designed. If there is no register constant, the reading gives directly the result desired.

With the exception of the right-hand dial, a pointer must always be read as indicating the figure that it has passed, and not the figure to which it may be nearest. For example, the tens, hundreds, and thousands hands of Fig. 28 each indicate *8* instead of *9*, but the units hand indicates *9*.

When a hand appears to be on a figure, its indication must be checked by the reading of the dial next to the right. If the hand of the tens dial, for instance, has just completed a revolution, the hand of the hundreds dial has passed the figure to which it appears to point; but if the hand of the tens dial has not quite completed a revolution, the hundreds hand must be read as not having reached the figure to which it apparently points. The same is true of a clock; the hour hand is not read as having reached a certain hour until the minute hand has made a complete revolution recording 60 minutes from the previous hour. As an example, there is room for doubt as to whether the hand of the *100,000* dial in Fig. 30 indicates *5* or *6*, unless it noted that the *10,000* hand has just passed zero, which shows that the reading of the *100,000* dial is *6*. Hands also sometimes become slightly misplaced, and then the correct reading of a misplaced hand must be ascertained by reference to the adjacent hand to the right.

The hands of adjacent dials rotate in opposite directions, and it is easy to mistake the direction of rotation of a hand. For this reason, a reading should always be checked.

63. Examples of Watt-Hour Meter Readings.—The following examples of watt-hour meter readings will serve to illustrate the general principles just explained. In each case, for convenience of reference, the pointer, or hand, on the dial at the left will be called the *No. 1 hand;* the hand on the next dial to the right, the *No. 2 hand;* and so on.

The No. 1 hand in Fig. 26 indicates *9*. There might be some doubt about the indication of the No. 2 hand; but, since the No. 3 hand has passed the *0* mark, the No. 2 hand indicates *5*. Since the No. 4 hand has not reached the *0* mark, the No. 3 reads *0* instead of *1*. The register, therefore, indicates 9,509 kilowatt-hours.

At first glance, the register shown in Fig. 27 appears to read 9 kilowatt-hours. If this were true, however, the No. 3 hand would be nearly to *1*. The true reading of the register is 9,999 kilowatt-hours.

The reading of the register shown in Fig. 28 is plainly 8,889 kilowatt-hours. The number nearest to the pointer is always taken as the reading on the right-hand dial; hence, *9* in this case instead of *8*.

The register shown in Fig. 29 indicates 20,090 kilowatt-hours. The No. 3 hand indicates *0* instead of *1*, because, as explained in connection with Fig. 26, the No 4 hand has not completed its last revolution. This meter has a register constant of 10, as indicated by the words *Multiply by 10.* Without the register constant, the reading would be 2,009; with the register constant, it is $2,009 \times 10 = 20,090$.

The register shown in Fig. 30 has a constant of 10 also. Its reading is $9,860,100 \times 10 = 98,601,000$ watt-hours, or 98,601 kilowatt-hours. The number beside each dial represents the number of watt-hours per revolution of the corresponding hand. For example, one revolution of the No. 5 hand represents 1,000 watt-hours; hence, each division of the dial represents 100 watt-hours. In a like manner, each division of any of the five dials represents one-tenth of the number marked beside that dial. Since each division of the No. 5 dial represents 100 watt-hours, two ciphers must be added to the number indicated by the hands. Multiplying by 10 adds another cipher, so there will always be three ciphers to add to the reading of the hands if the reading is to be expressed in watt-hours. If the reading is to be expressed in kilowatt-hours, these three ciphers are omitted.

64. Computing the Consumer's Bill.—To determine the consumption registered in a given time, the register reading at the beginning of the period should be subtracted from that at the end. The difference multiplied by the register constant, if any, will be the registration during the period in the unit marked on the register. This value multiplied by the cost per unit to the consumer will give the consumer's bill.

Example.—A consumer's watt-hour meter registering kilowatt-hours read, on May 1, 7,126, and on June 1, 7,492. The meter had a register constant of 10. What would be the consumer's bill at 9 cents per kilowatt-hour?

Solution.—	K.-W.-Hr.
Reading of watt-hour meter, June 1	7,492
Reading of watt-hour meter, May 1	7,126
Difference	366
Multiply by register constant	10
Consumption	3,660

Consumer's bill = 3,660 K.-W.-hr., at 9c. = $329.40. Ans.

INSTALLATION OF WATT-HOUR METERS

65. Location.—Watt-hour meters should be installed where they are easily accessible for reading or inspecting with a minimum of annoyance to the consumer on whose premises they are located. They should, as a rule, be placed not more than 7 feet from the floor, in a clean, dry, safe place that is free from vibration and magnetic influences. When there are a number of watt-hour meters, the distance between centers should be such that there will not be any influence of one on the other. A distance of 15 inches between centers is desirable.

66. Connections.—The method of connecting watt-hour meters in circuit varies with the make and the capacity of the meter, so that general instructions cannot be given. The makers furnish a diagram of connections that must always be carefully followed. The service wires in most types of meters enter on the left, and the load wires are connected on the right.

Reversing the direction of current flow in either the current or potential coils will reverse the direction of torque on the moving element. This would be evident at once in a two-wire watt-hour meter, as it would run backwards. In a three-wire watt-hour meter, one current coil might be reversed so as to act in opposition to the other, and the watt-hour meter would run backwards or forwards, depending on which field carried the heavier load; or if they were equally loaded, the meter would not run at all.

67. **Testing the Connections of Polyphase Meters on Three-Phase Circuits.**—If a polyphase meter is properly connected on a three-phase circuit, one element always makes the moving element run forwards; the other element makes it run forwards on power factors greater than 50 per cent. and backwards on power factors lower than that. Although the exact power factor of a load cannot be told unless it is measured, an induction motor running free will have a power factor under 50 per cent. and, when well loaded, will have a power factor greater than 50 per cent. Accordingly, a simple check of the accuracy of the connections of a polyphase watt-hour meter can be made by testing each element separately, disconnecting the circuit through the series coils of the other, but closing it outside the meter. If the watt-hour meter is in circuit with an induction motor running free, one element should cause forward rotation of the moving element and the other backward. On increasing the load on the motor to nearly full load, with the element causing forward rotation connected, the moving element should increase in speed; with the element causing backward rotation connected, the speed should decrease until the moving element stops and then starts with a forward rotation, as the power factor of the load passes from below 50 per cent. to above it.

68. **Testing Blocks.**—Testing blocks are sometimes used in the installation of watt-hour meters to improve the appearance of the installation, to prevent the possibility of tampering with the wires or meter, and to provide a ready means of connecting in instruments for testing the meter without interrupting the supply of energy in the circuit. A three-wire service cut-out and testing block in connection with a Fort Wayne induction watt-hour meter is shown in Fig. 31; the

cover is removed, showing the interior of the block. The service and house wires are brought in iron conduit into the top of the iron box in which the cut-out and testing block is placed and fastened to the upper binding posts, the service wires to the two outside posts *a* and the house wire of the same polarity to the adjacent inner posts *b*, with the neutral on the center posts *c*. The lower posts are for the corresponding wires on the meter. The clips in each line are for inserting a suitably connected testing plug, which will cross-connect the service and load wires so that the energy in the circuit will not pass through the meters, and will open the lines on the house side of the meter and connect in a circuit containing test instruments and a portable load without disturbing any of the permanent connections. A testing plug for a three-wire watt-hour meter can be used to open one of the service lines and connect the two current coils in series for testing on a two-wire circuit. An *adapter*, or *meter trim d*, conceals the wires from the testing block to the watt-hour meter. A cover that can be securely sealed is provided for the iron box containing the testing block. This device makes impossible any tampering with the wires, without breaking a seal, and provides a very safe and neat appearing installation.

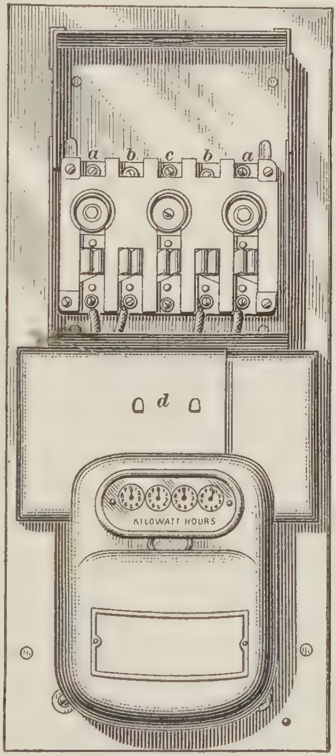


FIG. 31

SPECIAL METERS

PREPAYMENT METERS

69. Prepayment watt-hour meters are desirable for some classes of business, although they are not used very generally. The prepayment device is made either combined with the meter case or as a separate attachment. Prepayment meters are usually made to be operated with quarter-dollars. In one device, shown in Fig. 32, when a quarter is inserted, a knob *a* must be turned; this operation closes the circuit switch, if open, and moves the coin-registering mechanism. Several quarters may be deposited consecutively, and an indicator *b* on the device shows the number of coins standing to the consumer's credit. When the amount of electricity that is furnished for one quarter has been used, an escapement connected either mechanically or electrically with the meter register is released, and the coin indicator moves back one point; if no further credit remains, the circuit switch is opened. The actuating force that operates the device is a flat coil spring that is wound up by the turn of the knob when a coin is inserted. The coins drop through a guide *c* into a receptacle in the bottom of the case. The prepayment device is purely mechanical and does not affect the principle of the watt-hour meter.

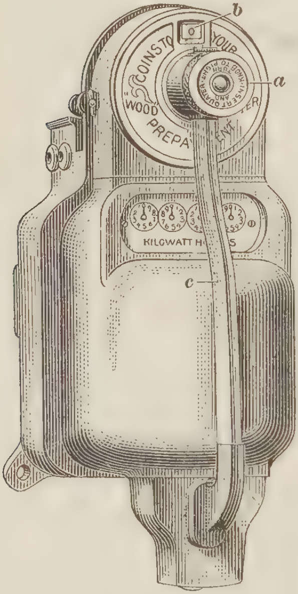


Fig. 32

TWO-RATE METERS

70. Uses.—Most central stations have their period of heaviest load for a few hours in the evening. During the daytime, the plant is lightly loaded, and a large part of the machinery is standing idle. In order to obtain a day load and thus work the plant to best advantage, some companies supply power during the daytime at specially low rates in order to induce customers to use electric motors. For measuring the power supplied to such customers, *two-rate meters* are sometimes used. A **two-rate meter** is one that records the power during certain hours of the day at a rate different from that at other hours. One of the earlier types was a regular Thomson recording watt-hour meter provided with two dials and two recording trains so arranged that a self-winding clock would throw either one or the other into gear with the meter shaft at the proper time. The energy recorded on the two dials was then charged for at different rates.

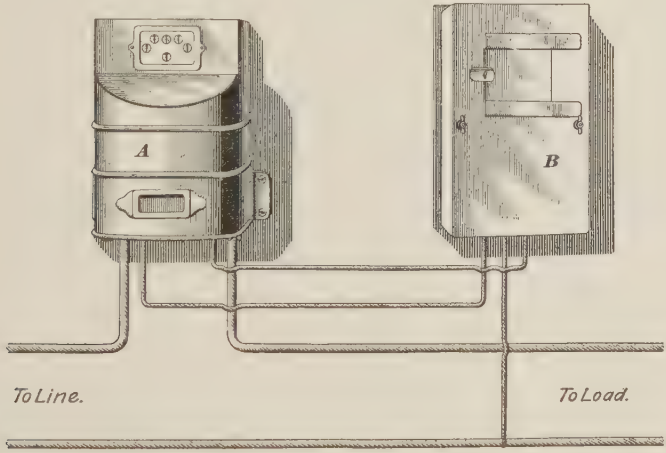


FIG. 33

71. Modern Two-Rate Meter.—In the later type, an ordinary Thomson watt-hour meter *A*, Fig. 33, with a single dial is used. Connected to the potential circuit of *A* is a self-winding clock mechanism contained in the case *B*. The case also contains a resistance, which is inserted in series with the armature of the watt-hour meter during those hours when a low rate prevails, thus making the meter run at reduced speed. The register will not indicate the correct amount of energy used, but rather the amount to be charged.

The same result can be obtained by connecting two separate meters in circuit with their current coils in series, and their potential circuits connected to a double-throw time switch, so that the potential circuit of one meter is opened and that of the other is closed during certain hours. Only the meter with the potential circuit closed will register, so that the readings of the two meters together will give the total energy supplied, separated according to the hours of service.

MAXIMUM-LOAD INDICATORS

72. Purpose.—The cost of supplying electricity from a central station, due to the fact that it cannot be economically stored but must be produced at the time needed, depends on two factors: (1) the cost of providing sufficient generating and distributing capacity to take care of the maximum amount required at one time; (2) the cost of continuing the actual supply of electricity.

The actual energy used by a consumer burning ten lamps for 10 hours is the same as that used by one burning 100 lamps of the same size for 1 hour; but the maximum demand on the generating and distributing system is ten times as large in the latter case, and the cost of supplying this service is consequently greater.

Differential systems of rates have been devised and have been quite generally adopted in order to proportion the charges for supplying electricity according to the conditions of use.

Numerous expedients have been adopted for fixing a consumer's maximum load, such as basing it on the average maximum load as ascertained for a certain number of consumers of the same class and with the same connected load; on a percentage of the connected load; on the floor area illuminated, or, in residences, on the number of rooms lighted. Although these have been quite satisfactory for certain classes of small customers, it is desirable in the case of large consumers to obtain an actual measurement of the maximum load. Several instruments are available for this purpose, and when used they are installed in the consumer's premises in conjunction with the watt-hour meter.

73. Examples of Maximum-Load Indicators.—An instrument for measuring the maximum ampere demand of appreciable duration in any circuit, is shown in Fig. 34. This instrument, known as the **Wright demand indicator,** consists essentially of a hermetically sealed, **U**-shaped glass tube, hidden partly by the scale in the illustration, that has bulbs *A* and *B* on the ends and an overflow tube *C*. The current passes between the terminals *D* and *E* through a resistance band *F* placed around the bulb *A*. The **U** tube is filled with a liquid to a level with the point where the tube *C* joins it. When heated by the passage of current through the resistance band *F*, the air in the bulb *A* expands and consequently forces the liquid down in the left-hand and up in the right-hand side of the **U** tube, so that it overflows into the tube *C*, where it will remain until the tube is reset. Any increase in current will force over more liquid; thus, the height of the liquid in the tube *C* can be calibrated to show the maximum current that has passed through the indicator.

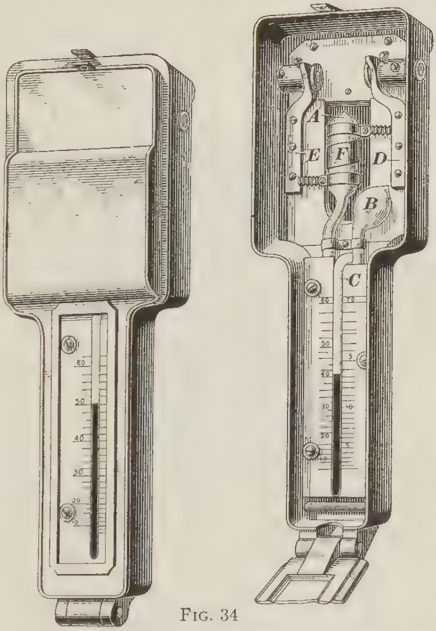


FIG. 34

The Wright indicator is slow-acting, recording about 90 per cent. of the load in 4 minutes, 97 per cent. in 10 minutes, and all of it in about 30 minutes. The **U**-shaped tube is mounted on an arm that can be swung up after the reading has been taken, thus emptying tube *C* into the **U**-shaped tube.

74. A **polyphase maximum-watt demand indicator** consists of a polyphase watt-hour meter with both elements acting on the top disk, and a strong damping system acting on the lower disk to provide the necessary time lag. The single graduated dial has two pointers. One pointer indicates the energy passing through the instrument at any time, subject to a correction due to time lag; the other is driven by the first and is left at the highest position reached, thus indicating the maximum energy that has passed through the instrument since it was last set. The time lag for 90 per cent. of full registration can be set at 1 to 5 minutes.

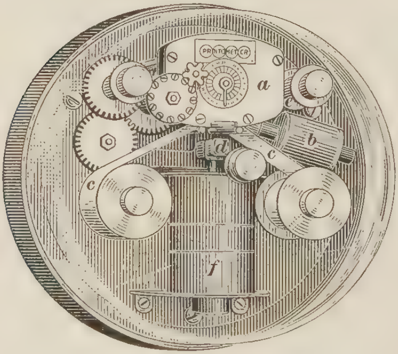


FIG. 35

75. The **printometer** is an automatic recording mechanism that can be connected to any integrating type of watt-hour meter and will print in plain figures on a paper tape a reading corresponding to that of the meter at any desired interval, such as 5 minutes, 30 minutes, or 1 hour. The difference between successive readings, when multiplied by the proper constant, will give the energy registered by the meter during the given interval, and from this can be obtained the average demand for each interval, and consequently, the maximum average demand over that interval during a day or a month.

The device is shown in Fig. 35. A set of type wheels behind plate *a* is operated by the armature of a solenoid *b* energized by current through an electric contact placed on the register of a watt-hour meter. The movement of these wheels is therefore proportional to that of the watt-hour meter register and, consequently, to the flow of energy through the watt-hour meter. The reading of the type wheels is printed on a paper tape *c* by means of a rubber platen *d* and a copying ribbon *e*, the platen being operated by an electric solenoid *f* whose circuit is closed at regular intervals by an auxiliary contact-making clock.

76. The **maxicator,** Fig. 36, is a maximum-load indicating device that is attached to a watt-hour meter in place of the regular register. It has four dials, like that of the watt-hour meter register, for registering the total consumption and, in addition, a dial of larger diameter for indicating the maximum registration during any ½-hour interval. The time interval is obtained by means of a clock, or, on an alternating-current circuit, by means of a contact-making, self-starting induction motor, which at ½-hour intervals completes the circuit through a solenoid that is mounted on the back of the maxicator and performs the operation of resetting. The arm that drives the large hand is reset to zero at the end of every interval, leaving the hand at the highest point reached during any period since it was last read and reset.

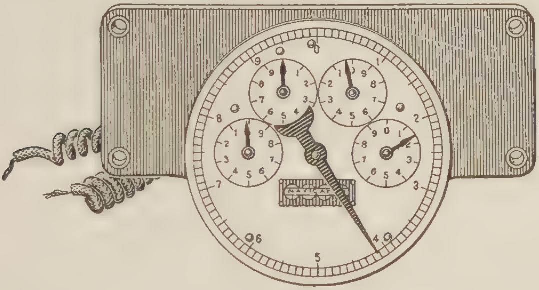


FIG. 36

77. Graphic recording instruments, which trace on a chart a line the height of which is at all times proportional to the load passing through the instrument, are also available for ascertaining the maximum load. These instruments are not, however, generally used in connection with watt-hour meters.

VOLTAGE REGULATION OF ALTERNATING-CURRENT CIRCUITS

NECESSITY OF EMPLOYING MEANS OF REGULATION

DESIRABILITY OF GOOD REGULATION

USER'S STANDPOINT

1. Perfect voltage regulation exists in a system when the voltage at the terminals of each lamp is maintained constant. This voltage need not be uniform at all lamp terminals, but if perfect it would not vary at any given lamp. Perfect regulation, however, is an ideal condition not attained in practice. The best that is usually done is to regulate within 1 or 2 per cent. of the rated voltage, and this is called good regulation.

2. Good regulation is desirable for both the user and the producer of electricity. It is absolutely essential for steady incandescent lights, because a very small change of voltage produces a very decided change in the illumination. A measure of light is the *candlepower*, and curve *a*, Fig. 1, shows how the light from an ordinary carbon-filament lamp varies with varying voltage. From this curve it is seen that at 98 per cent. of normal voltage the candlepower decreases to slightly less than 90 per cent. normal candlepower, while at 102 per cent. of

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normal voltage the candlepower is 112 per cent. of normal. Fig. 2 shows part of a chart on which the full line *a* indicates the exact voltage of a circuit at each instant during a period of 3½ hours, and the dotted line *b* the corresponding candlepower. The voltage line was drawn by a *graphic voltmeter*, an instrument in which a pen automatically traces a line corresponding to the voltage, on a moving strip of a paper marked to indicate volts and time. The paper moved from left to right, making the time indications read from right to left. The values for the dotted line *b* were calculated by the aid of the candlepower curve in Fig. 1.

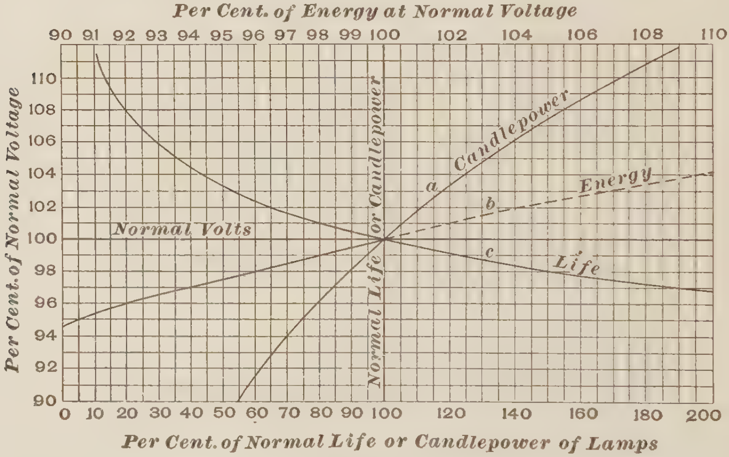

FIG. 1

The extreme variation of candlepower with varying voltages, as indicated by curve *b*, Fig. 2, shows very graphically why steady voltage is desirable for good lighting with carbon-filament incandescent lamps. The metallic-filament lamps are a little better in this respect, but they too need steady voltage for good results.

Steady voltage is sometimes essential for satisfactory motor operation where the speed must be constant. Such conditions are not common, however; in ordinary motor applications the changes of speed with small variations of voltage are not seriously objectionable.

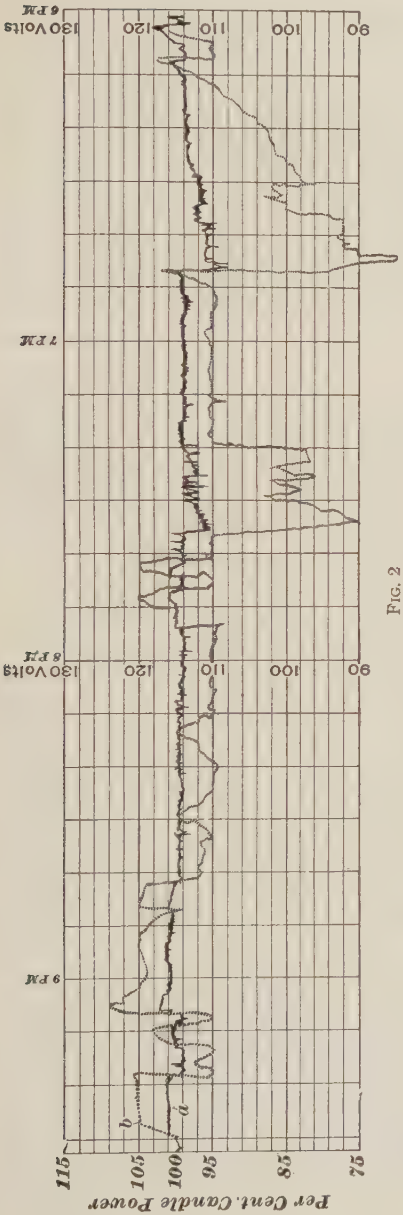

Fig. 2

PRODUCER'S STANDPOINT

3. In comparison with poor voltage regulation, steady voltage gives (1) better illumination; (2) increased sale of energy; (3) decreased lamp renewals; and (4) minimum transformer losses.

The first condition has already been explained, and is as important to the producer as to the user. It is the most important reason for maintaining steady voltage, and is one of the causes of the second condition, because good illumination makes satisfied users and increased sales of electricity. The second, third, and fourth conditions are important to central stations; especially is the third condition important to those stations giving free lamp renewals, as do most of the leading stations.

4. Energy Sales and Lamp Renewals.—Good voltage regulation results in increased sale of energy because of increased number of customers and increased meter readings for a given number of connected lamps.

The resistance of the lamp filaments remains nearly constant during the voltage changes, and the current therefore varies directly with the voltage, making the energy supplied for lighting vary approximately as the square of the voltage. Curve *b*, Fig. 1, shows the effect on the energy output of operating carbon-filament incandescent lamps at different voltages. At 98 per cent. of normal voltage the output is only 96 per cent. of normal, while at 102 per cent. of normal voltage the output is 104 per cent. of normal. Both these figures are approximate, owing to the slight change of resistance of the lamp filament with change of voltage.

Curve *c*, Fig. 1, shows the effect of change of voltage on the useful life of a carbon-filament lamp. At 98 per cent. of normal voltage the life is increased to 150 per cent. of normal, and at 102 per cent. of normal voltage the life is decreased to 65 per cent. of normal.

The station therefore gains in power output by operating at increased voltage, but loses in lamp renewals; conversely, it loses in output by operating at reduced voltage, but gains in lamp renewals. Whether these gains and losses compensate each other may be uncertain, but it is certain that most satisfactory illumination occurs at steady normal rated voltage.

5. Transformer Losses.—Since the losses in transformers increase as the square of the voltage, a very little increase in the voltage of a large system having many transformers connected means a very considerable increase in total losses. Such losses are worthy of especial consideration, because excess voltage is most likely to occur during periods of low load when the station is receiving small compensating return for the increased loss.

However, it is not usually the slow and steady changes of voltage that are so objectionable, but rather the rapid changes or fluctuations, as shown in Fig. 2. These changes are what make the lights flicker, and flickering lights cause more prompt objections than dim lights, though neither are desirable.

CAUSES OF POOR REGULATION

6. Load Characteristics.—The primary cause of poor voltage regulation is unsteady load. This cause affects the speed and voltage characteristics of the generating equipment as well as the voltage loss in transmission. Good speed regulation of prime movers (engines, turbines, waterwheels, etc.) is therefore very important, as a change in the driving speed produces a proportional change in the generator voltage. Good speed regulation is obtainable with modern machinery by means of automatic devices.

7. Generator and Transformer Characteristics. However close may be the speed regulation of the driving power, a generator with poor regulation will not deliver steady voltage with varying load. Unless the generator is very carefully designed and adjusted, some change of voltage with change of load must be expected, even though the driving speed is perfectly steady.

Alternators and transformers are always subject to such voltage changes, depending on both the character of the load and the design of the apparatus. The inherent regulation of alternators when carrying non-inductive load is much better than when carrying inductive load. Incandescent lamps are an example of non-inductive load, and motors an example of inductive load. The regulation of an alternator or a transformer depends on both the resistance and the inductance of its windings. Care in selecting alternators and transformers is therefore an aid in obtaining good regulation.

8. Voltage Drop in Transmission.—With perfect regulation at the generator terminals, however, the regulation at the distant lamp terminals may be far from perfect, owing to voltage drop in the distributing circuits, or feeders. This voltage drop is proportional to the current, and since the several feeders may be carrying entirely different loads, it may be necessary to regulate each circuit independently of the others in order to obtain satisfactory lighting.

The voltage at the station ends of the feeders must be enough above the lamp voltage to compensate for the voltage drop in the circuit to the lamps. During periods when the largest number of lamps are burning the voltage drop is greatest, and the voltage at the station end of the feeder must therefore be highest.

METHODS OF OBTAINING GOOD REGULATION

ALTERNATOR REGULATORS

9. In alternating-current practice, voltage-regulating devices of two general types are employed: *alternator regulators*, which operate by controlling the field strength of the generators, and *feeder regulators*, which operate on the induction principle; that is, as transformers, with a variable ratio of transformation. Either type can be arranged for either hand or automatic operation. Hand operation is satisfactory if the regulation is simply to compensate for slow and gradual voltage changes; but for frequent and rapid changes, such as are common when the circuits are carrying current to motors, automatic devices must be employed.

10. *Hand control* of alternator regulators is nothing more than the manipulation of field rheostats. The success of such control depends on the frequency and the extent of adjustments and on the faithfulness and alertness of the station attendants. *Automatic control* is accomplished by arranging a contact-making voltmeter and relay contacts to open and close a current path, or short-circuit, around the field rheostat of the exciter. The rheostat is set to reduce the alternator voltage considerably below that desired, whereas, if the short-circuiting path were closed continuously, thus cutting the rheostat out of circuit, the voltage would rise too high.

The automatic regulator, however, cuts the rheostat out of circuit when the voltage falls too low, and into circuit again when the voltage rises too high. By continuing this process, the voltage is automatically regulated within close

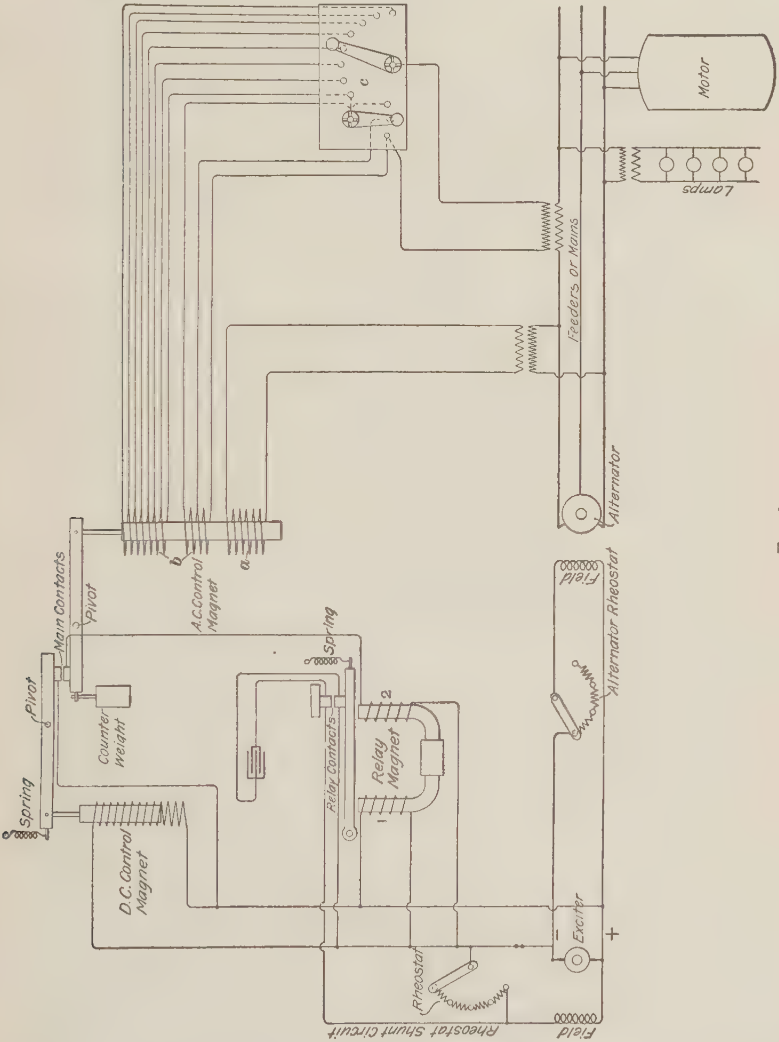

FIG. 3

limits. This regulator is known as the **Tirrill type,** and is essentially the same as described in *Direct-Current Generators.*

11. Fig. 3 shows connections of a Tirrill regulator for alternating-current generators. The contact-making voltmeter consists of two control magnets operating pivoted levers that carry the main contacts. The excitation of the direct-current control magnet depends on the exciter voltage; as this voltage falls, the core of the magnet is drawn up by a spring until the main contacts are closed.

The main contacts are called *floating contacts*, because the position at which they close varies with the load on the alternator. The alternating-current control magnet serves to regulate this position automatically. The excitation of coil *a*, Fig. 3, depending on the alternator voltage, tends to raise the core of the alternating-current control magnet and thereby allow the lower main contact to be drawn down by the counterweight; the excitation of coil *b*, depending on the alternator current, tends to lower the core and thereby raise this contact. Thus the higher the alternator current and the lower the voltage, the higher will be the position in which the main contacts close, and the less will be the action of the direct-current control magnet necessary to close them. A contact-making device *c* serves to adjust the relative effects of coils *a* and *b*, and can be set so that the alternator voltage will be maintained at a higher or a lower value, according to the distance from the alternator to the point where a given voltage is required.

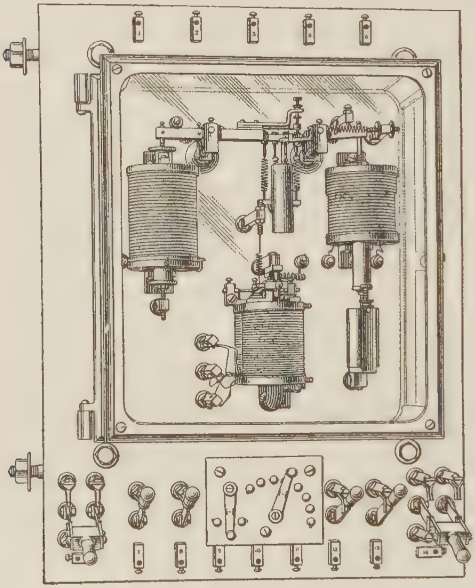

FIG. 4

The main contacts serve to control the circuit through one winding of the relay magnet, because they are too delicate to open and close the short circuit around the field rheostat.

When winding *1* alone is excited, the relay contacts are held open; but when winding *2* is also excited, owing to the action of the main contacts, it acts differentially with winding *1*, thus weakening the relay magnet; the relay contacts then close automatically, owing to the action of a spring, thus short-circuiting the field rheostat.

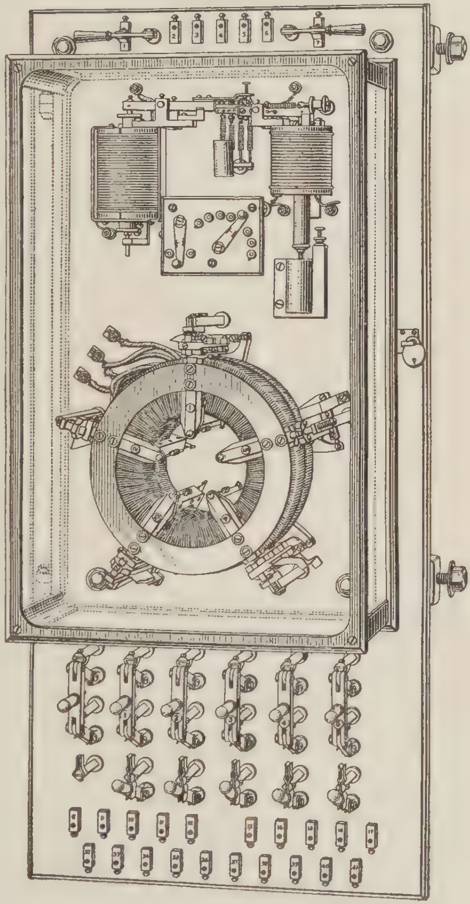

Fig. 5

12. On reduced alternator voltage, magnet coil *a*, Fig. 3, weakens, and coil *b* draws its core down, closing the main contacts; the closing of the relay contacts follows immediately, cutting all control resistance out of the exciter field circuit. The exciter voltage promptly rises, strengthening the pull of the direct-current control magnet and opening the main contacts; the relay contacts then open, inserting the control resistance into the exciter field circuit. The contact levers vibrate continually; they are light and respond quickly to changes of voltage, thus maintaining the voltage steady within narrow limits. The relay contacts are protected from excessive sparking by a condenser, and both sets of contacts are provided with tips not readily affected by the slight sparking that occurs in practice.

13. Fig. 4 shows the front of an alternator voltage regulator for use with one exciter, as explained in connection with Fig. 3. The two control magnets are in the upper part of the glass case, Fig. 4, with the floating contacts between, and the relay magnet with the two windings on one straight core is in the lower part of the case. Fig. 5 shows the arrangement of relays when a regulator is to be used with several exciters. Any number of exciters can feed into one set of bus-bars, and from this set any number of alternators can be excited. The field of each alternator is adjusted independently of the others by means of its rheostat until the alternators share the load properly, after which the automatic regulator with a relay for each exciter and an alternating-current control magnet in connection with the circuit from one alternator will keep the voltage of all the alternators steady.

FEEDER REGULATORS

14. A **feeder** is a circuit leading from a source of supply or from a center of distribution of electricity to a center nearer the consuming devices, or to a group of such devices. Thus, one feeder may lead from the power station to a switchboard in a large office building or factory, and other feeders may lead from this board to different parts of the building.

If all feeders from a power station carried current for lighting loads of the same character, the generator voltage regulators could take care of the whole system, but such conditions rarely exist. The districts supplied by most stations may be considered in three classes, namely, business, manufacturing, and residential, and the maximum currents in feeders to these districts do not occur simultaneously.

Obviously, the station voltage cannot be raised to compensate for line drop in the feeder carrying maximum current without supplying excess voltage to feeders on which the load is less than maximum. Furthermore, power load and lighting load must, in many cases, be supplied through the same feeder, while possibly other feeders are carrying lighting load only, rendering independent feeder voltage regulation essential.

15. A **feeder regulator** is a device for adjusting the voltage of alternating-current circuits independently of the alternator regulators or other feeders of the same system. All feeder regulators may be called *variable-ratio transformers*. In practice, two types are supplied; these are known as the *induction type* and the *switch*, or *step-by-step*, *type*. In both cases the winding corresponding to the primary of a transformer is in shunt with the circuit that is being regulated, while the winding corresponding to the secondary is in series with the same circuit.

In the induction regulator, the core and winding forming the primary is rotatable, so that any part of the flux generated by the primary can be made to pass through the stationary secondary winding in either direction. By rotating the primary, the regulator can thus be made to boost or to lower the voltage of the circuit any desired amount up to the limit of the regulator capacity. In the switch-type regulator, both the primary and the secondary are stationary, and any part of the secondary can be connected in circuit in either direction by means of a switching device, thus boosting or lowering the voltage.

INDUCTION FEEDER REGULATORS

16. Single-Phase Induction Regulators.—Fig. 6 shows the arrangement of cores and windings of a small single-phase induction regulator. The stationary cylindrical shell, or core, has radial slots in which the secondary winding a is placed. Concentric with this shell is a core, or armature, with slots containing the primary winding b and a short-circuited winding b'. This core can be rotated 180°, and the flux set up by the primary winding can therefore be made to take any desired direction with reference to the flux set up by the secondary winding, from direct agreement with it to direct opposition to it. Both fields are alternating, and reference to their agreement and opposition means instantaneous direction. If they oppose, the feeder voltage is boosted; if they agree, the feeder voltage is lowered.

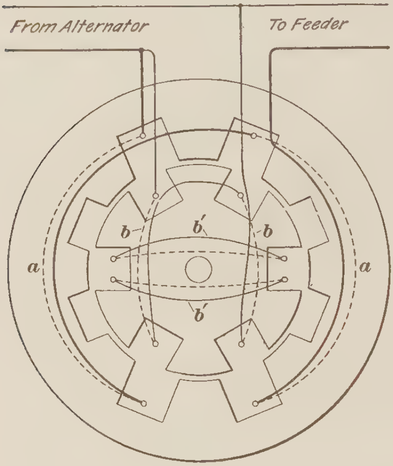

Fig. 6

Fig. 6 shows the primary core in position for maximum lowering of the feeder voltage; rotating the core 180° gives the position of maximum boost of feeder voltage. The primary core can take any intermediate position between these two extremes, giving any desired voltage adjustment from maximum boost to maximum lowering.

Larger induction regulators differ from those shown in Fig. 6 by the use of more slots and coils; Fig. 7 shows a rotor with several coils, and Fig. 8, the outside of the secondary core without the tank in which it is enclosed when in operation.

17. The purpose of the short-circuited winding b', Fig. 6, is to keep the reactance of the regulator low. With the primary and secondary coils in the position shown for maximum lowering, each encloses all the flux set up by the other; this is true also when the primary core is in the position of maximum boost. In either of these positions, the primary coil serves to keep the reactance in the secondary circuit low. As the

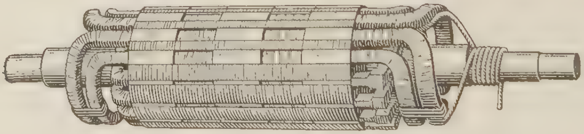

Fig. 7

core is rotated from either position toward the neutral, the primary coil encloses less of the flux set up by the secondary, and the short-circuited coil simultaneously encloses more of it.

In passing from either of the maximum positions to the neutral position, therefore, the current in the short-circuited coil increases from zero to its maximum at the same rate as the influence of the primary coil decreases, so that the total ampere-turns of the primary and short-circuited coil combined is approximately equal to the ampere-turns of the secondary. The setting up of heavy flux by the current in the secondary coil is thereby prevented by the combined effect of the primary coil and the short-circuited coil, and the reactance is kept low regardless of the position of the rotor.

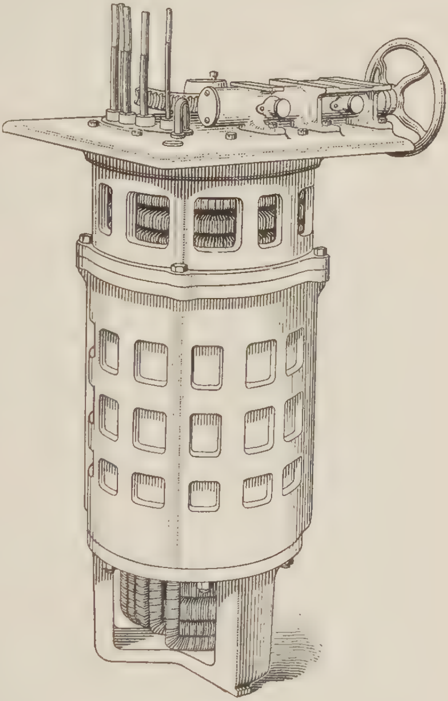

FIG. 8

18. The vertical distance between the curves in Fig. 9 represents voltage drop; these curves, from actual tests, thus show that the voltage drop in the regulator is practically constant for all positions of the rotor; the inductive drop must therefore be practically the same for all positions. The short-circuited coil tends to keep the losses in the regulator constant. The losses in induction regulators are low; hence, the output must be nearly equal to the input. If it is assumed that there are no losses and that the range of adjustment is from 10 per cent. boost to 10 per cent. lower, the extreme conditions on a 100-volt, 100-ampere circuit are as shown in Fig. 10, (*a*) being for regulator boosting and (*b*) for regulator lowering.

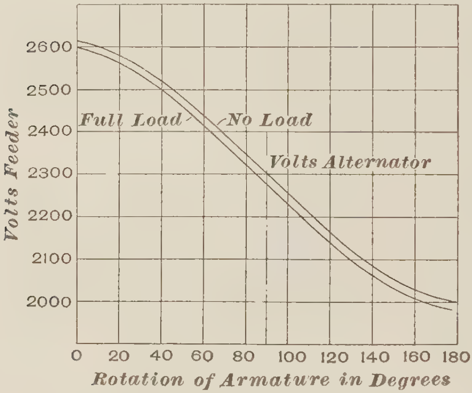

FIG. 9

19. Polyphase Induction Regulators.—The polyphase induction regulator has many features of construction similar to the single-phase regulator. Both the stationary and rotating elements, however, have as many sets of coils as there are phases in the circuit. The windings are distributed, giving the parts very much the appearance of those of an induction motor, as is shown in Figs. 11 and 12, which illustrate respectively the rotor and the stator.

In a polyphase regulator, the induced voltage in the secondary winding is constant, but by rotating the primary this induced voltage can be made to take any desired phase relation to the line voltage, as shown vectorially in Fig. 13, in which *a b* represents the normal voltage of one phase of a balanced polyphase system, and *b c*, *b e*, etc. represent the induced voltage in the regulator. By rotating the primary, the induced voltage can be added directly to the line voltage, giving maximum volts *a c*; it can be subtracted, giving minimum volts *a d*, or its phase

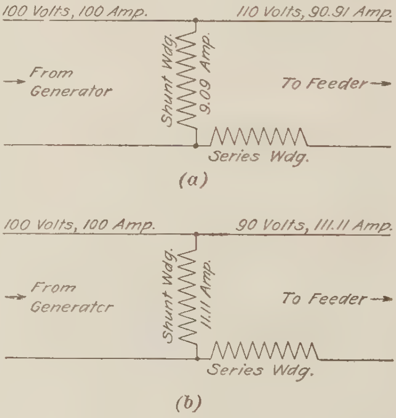

FIG. 10

may be made to take any intermediate position, *b e*, *b f*, *b g*, giving any adjusted line voltage, as *a j*, *a b* (neutral), and *a h*.

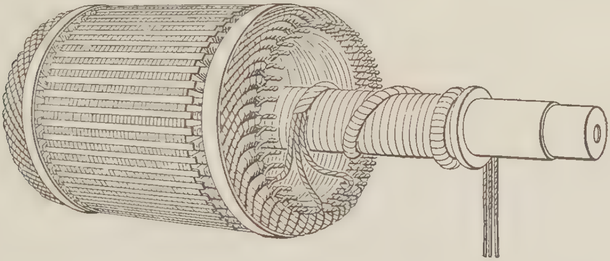

FIG. 11

20. Performance.—Induction feeder regulators are seldom used for other than lighting circuits that have high power factor; the power factor of the regulator, although low, has very little effect on that of the circuit. Such regulators have fairly high efficiency, ranging from 92 to 97 per cent., according to size. They handle so small a part of the energy of a circuit that their losses are an inappreciable portion of the total energy and their effect on the efficiency of the distribution system is accordingly small.

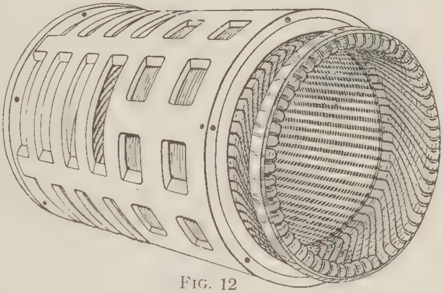

FIG. 12

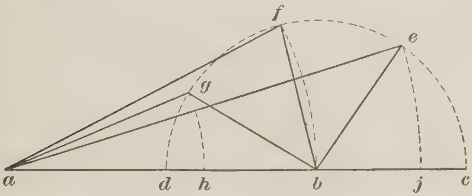

FIG. 13

21. Operation. Induction regulators can be arranged for operation by means of hand wheels or by motors manually or automatically controlled. Hand-wheel control applies where only occasional changes are essential, and where the regulator is within easy access for an attendant.

Hand-controlled motors can be connected with the switchboard so that closing a double-throw switch on the board will start the motor in a direction to raise or lower the voltage, according to the way in which the switch is closed. This method is applicable where changes are not too frequent and the voltage is under constant supervision.

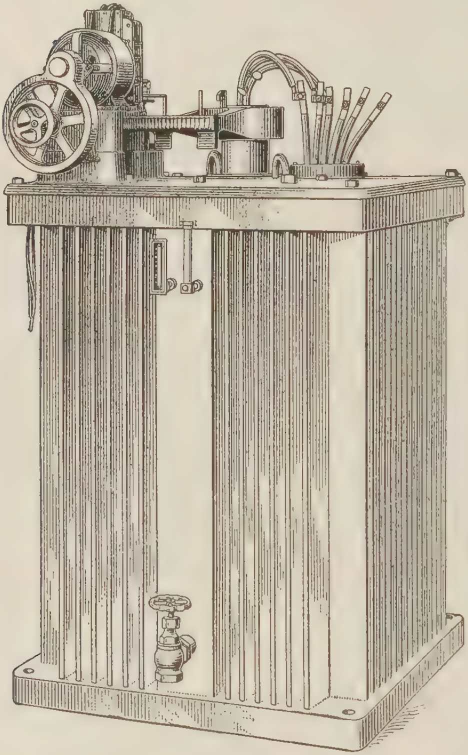

FIG. 14

Automatic motor operation by means of contact-making voltmeters with relay switches for closing and opening the motor circuits has the most general application. Fig. 14 shows a motor-operated polyphase regulator, the arrangement of the motor and reducing mechanism being typical of all; the speed reduction is obtained by means of both spur gears and worm-gears. The worm meshes with a segmental gear attached to the rotor shaft. The motor rotates several hundred times to a single rotation of the regulator armature. Preferably, the motor is of the polyphase squirrel-cage type, whether the regulator is polyphase or single phase. Such motors have the strong starting characteristics and the low inertia essential for most successful operation. An electric brake is arranged to release when current is applied to the motor and to set when the current is shut off, thus preventing overrunning, or "hunting." With all automatic motor-operated regulators limit switches are employed to open the motor circuit automatically when the rotating element of the regulator has reached the limit of its travel in either direction; the opening of either switch does not prevent the other from closing to operate the motor in the reverse direction of rotation.

22. The *contact-making voltmeter*, or *potential relay*, consists essentially of an electromagnet with moving and stationary contacts arranged to close one of two circuits whenever the line voltage is low or high. Fig. 15 shows one form of a potential relay. The magnet *a* has a movable core attached to one end of a pivoted lever *b*. The other end of the lever carries contact points *c* of special non-arcing alloy, that touch corresponding stationary points whenever the lever is tilted from the horizontal position. The lever is balanced by a helical, or coiled, spring *d* and the weight of the magnet core; this core rises when the magnet is excited and falls when the magnet weakens, thus closing or opening contacts.

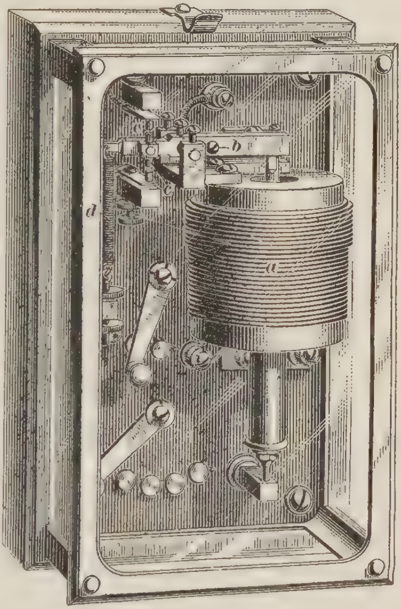

Fig. 15

The magnet coil has a compound winding similar to the alternating-current control magnet in a Tirrill regulator, as shown in Fig. 3. Means are also provided for adjusting the relative effects of the shunt and series windings, so that close voltage regulation can be maintained at a center of distribution some distance from the regulator. Another type of potential relay employs a magnet coil with only one winding, and connects this winding in series with the secondaries of two transformers, the primaries of which are respectively in shunt and in series with the circuit to be regulated. Typical connections of such an arrangement are shown in Fig. 16.

23. The compensator includes a series transformer, and, in connection with the shunt transformer and a resistor, maintains at the terminals of the primary relay a voltage proportional to that at the distributing end of the feeders. A compensator with a resistance element alone can be set to maintain constant voltage with any constant power factor;

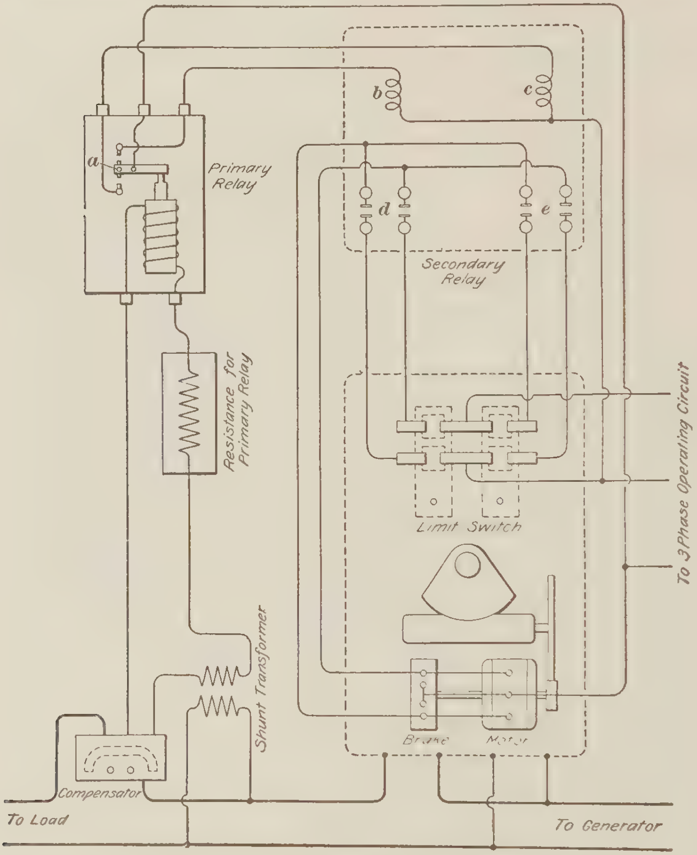

Fig. 16

a compensator with both resistance and reactance elements can be set to take care of a load with varying power factor.

24. The *secondary relay* is essentially a double-pole, double-throw switch operated by two alternating-current magnets, one serving to close the contacts in one direction, and the other in the opposite direction, depending on the action of the potential relay. Fig. 17 shows one form of such a switch; the butt-type stationary and moving contacts are visible through the opening in the lower part of the case, and a part of the laminated magnetic circuit can be seen through the opening in the upper part.

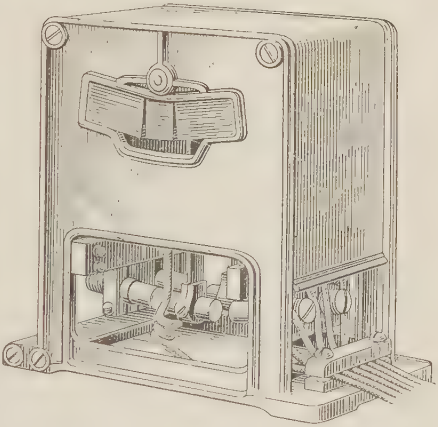

Fig. 17

25. The primary relay controls the circuits of the operating coils of the secondary relay, and this latter relay closes one phase of a circuit to the motor, starting it in a direction corresponding to the action of the primary relay. The motor then turns the primary core of the regulator until the voltage reaches the right adjustment, when the relays again operate and open the motor circuit. The limit switch operates only at the end of the primary core travel in either direction.

For example, if the voltage at the distributing point falls too low, the primary relay contact *a*, Fig. 16, closes in the upper position, placing the secondary relay coil *b* across one phase of the operating circuit. The secondary contacts *d* are thereby closed, completing the three-phase connection to the motor and starting it in one direction. High voltage at the distributing point causes the primary relay contact *a* to close in the lower position, thus placing the secondary relay coil *c* in circuit, closing contacts *e* and starting the motor in the opposite direction.

SWITCH TYPE REGULATORS

26. A **switch type regulator** consists of an autotransformer, or compensator, with which the circuit from the alternator has permanent points of contact, and the feeder circuit one permanent and one adjustable contact. Fig. 18 shows simplified connections; *a b* represents the transformer winding of which *a c*, the portion shunted across the supply circuit, may be called the primary, and *a b* the secondary; *d* is an adjustable contact that can be connected with different points of the secondary.

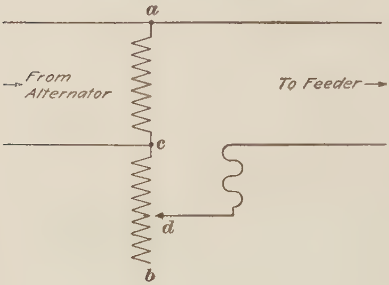

FIG. 18

27. Hand Operation.—Fig. 19 indicates more clearly the true conditions for a hand-operated dial-switch regulator in commercial service. By means of the dial switch the feeder circuit can be connected to any point of the secondary coil, and by means of the switch *a* the connections of this coil can be reversed, thus giving boosting or lowering effect to the feeder voltage in as many steps as there are contacts on the dial switch. For example, with switch *a* closed as indicated by the arrow, and the dial switch on contact *1*, maximum boosting effect is obtained.

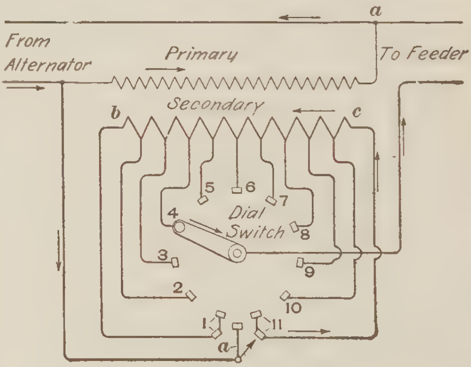

FIG. 19

As the switch passes over contacts *2*, *3*, *4*, etc., cutting the secondary out of circuit, the boosting effect is decreased until at contact *11* it becomes zero. In continuing the movement of the dial switch from contact *11* to contact *1*, switch *a* is automatically thrown to the left, closing the circuit directly with contact *1* and thus reversing the connections of winding *b c*. Further movement of the dial switch over contacts *2*, *3*, *4*, etc. cuts portions of this winding into circuit in the reverse direction, thus lowering the voltage. Maximum lowering is obtained when *a* is in contact with *1* and the dial switch is on contact *11*.

Conditions necessary for the success of such a regulator are that the moving contact of the dial switch must not bridge any two stationary contacts; all movements from contact to contact must be by snap action, occurring so quickly that although the circuit is momentarily broken, no effect can be observed on the lights. This action is accomplished by means of compression springs; while the handle is being turned a retarding device holds the moving contact stationary until the spring is compressed enough to force it loose and snap it to the next stationary contact.

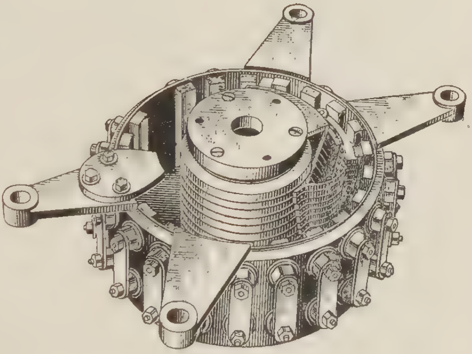

FIG. 20

28. Automatic Operation.—Automatic regulators of the switch type operate so frequently that the snap movement of contact is not practicable. Instead, the switching device is so arranged that connections are changed without opening circuits. Fig. 20 shows a dial switch of an automatic regulator and Fig. 21, connections and the principle of operation. The upper part of Fig. 21 represents ends of the series of contact bars *e* and collector rings arranged respectively on the inner and outer surfaces of two concentric cylinders, and the lower part shows a side view of the rings and a development of a part of the interior of the cylinder on which the bars are arranged vertically. Both the collector rings and the vertical parts are stationary; the only moving part is a switch arm carrying a series of contacts that interconnect rings and bars. Each contact is insulated from the others, and each consists of a brush at one end sliding over a collector ring, and a finger at the other sliding over the successive bars. The fingers are arranged in a diagonal row *g*, as shown in the lower part of Fig. 21; the whole row, together with the rings and preventive resistance, forms a closed circuit between two adjacent bars, a single finger being too short to bridge the opening between bars. In every position of the switch arm, the circuit of one step of the transformer secondary is therefore closed through the bars, the moving contacts and rings, and the preventive resistance, which limits the current in this circuit to a safe value. By thus keeping the connections unbroken, very fine adjustments and smooth changes are possible.

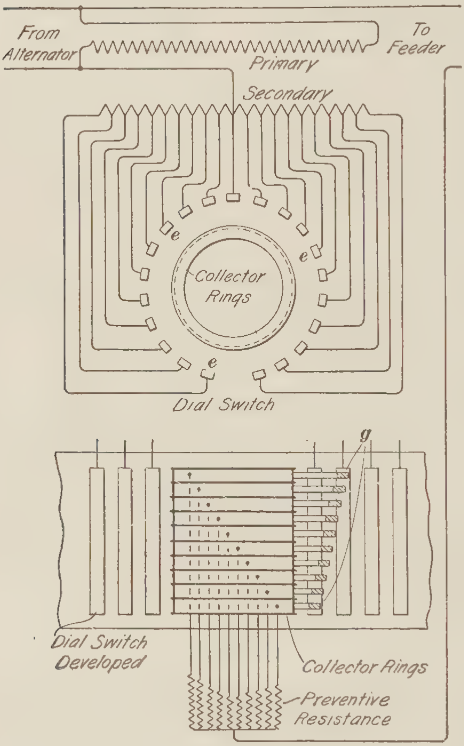

FIG. 21

29. The dial switch is mounted under the cover of the regulator and above the transformer, as shown in Fig. 22, and is operated by a small motor mounted above the cover.

The motor runs continuously while the regulator is in operation, and its motion is transmitted through magnetic clutches, one at each end of the motor shaft. If the feeder voltage departs from standard, a contact-making voltmeter closes a circuit through one or the other of the clutch magnets, bringing a clutch into operation and causing the contact arm of the dial switch to move so as to obtain the proper voltage adjustment. The moving part has very small inertia, making quick movements and close regulation possible.

Only the part of the secondary circuit needed for regulation is in circuit at any time, thus minimizing the losses. The power factor is very near unity, both the efficiency and the power factor being better than regulators of the induction type. However, either regulator handles so small a portion of the total energy of the circuit that its efficiency and power factor have but little influence on those of the circuit.

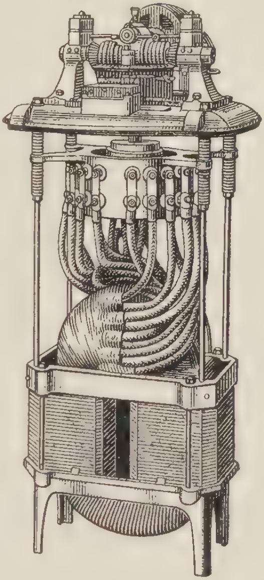

FIG. 22

APPLICATION OF FEEDER VOLTAGE REGULATORS

30. Feeder regulators are applied to single-phase circuits, as described in the foregoing discussion, one regulator to each circuit. Unbalanced polyphase circuits require a single-phase regulator for each phase requiring regulation. In many cases, all the lighting of a given section can be connected to one phase of a polyphase circuit, and a regulator used in that phase only, leaving the other phases unregulated. Balanced polyphase circuits are the only legitimate field for polyphase regulators.

ELECTRIC LAMPS

(PART 1)

INTRODUCTION

CLASSIFICATION OF ELECTRIC LAMPS

1. There are three methods in common use for producing light by electricity: (1) by incandescent lamps; (2) by arc lamps; (3) by incandescent tubes. Although each of these methods may be used for either interior or exterior lighting, the first is used mainly for interior work, the second largely for street work, and the third almost exclusively for interiors.

2. In the **incandescent lamp,** light is produced by a continuous conductor of high resistance heated to a high temperature by the current in it. The current in any conductor causes a loss of electrical energy dependent on the resistance of the conductor and the current. The electrical energy thus lost reappears as heat, which raises the temperature of the conductor. In the incandescent lamp the resistance is very high and the conductor is small, so that the temperature is raised to such a point that light is produced. The conductor is said to be incandescent, or glowing, and from this is derived the name of the lamp.

Incandescent lamps may be operated from either direct or alternating-current circuits with the same results. With alternating current, the brilliancy of the filament is actually varying very rapidly in synchronism with the current, but the eye does not ordinarily detect these variations unless the frequency is below 25 cycles per second.

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3. In the **arc lamp,** the light is produced by the heating of a conductor that is not continuous, but includes a short air gap. The current passes across this air gap in the form of an *arc*, as it is called, between two *electrodes*. Because of the high resistance of the air gap, the electrodes or the arc or both become heated to a higher temperature than that of the incandescent lamp, and an intense light is given off.

Arc lamps are designed for either direct or alternating current, but, unlike incandescent lamps, cannot be operated interchangeably on both. Frequencies below 25 cycles produce noticeable flickering and are unsatisfactory for arc lamps.

4. Tube lighting combines the elements of both incandescent and arc lighting. In one type of tube lamp the current in a tube from which most of the air has been exhausted heats mercury to the point of vaporization and causes the resulting mercury vapor to become incandescent. In another type an electric discharge takes place through the partial vacuum, much like a lightning discharge, and light is given off direct from the discharge, or arc, thus established.

The tube using mercury vapor can be operated with either direct or alternating current, according to the design of the lamp, while the vacuum tube is operated with alternating current only, because the high voltage required is impracticable with direct current.

5. Arc lamps and incandescent tubes are, in a sense, both incandescent lamps; but the term *incandescent lamp* as commonly used refers to the type employing a slender conductor of high resistance, called a *filament*.

PRELIMINARY DEFINITIONS

6. Luminous Efficiency.—The energy radiated as light from most artificial light-giving sources is but a very small fraction of the total energy supplied. Any source of light radiates energy that affects the eye, and is called light, and energy that is invisible. The first is called *luminous radiation*, and the second *obscure radiation*. If A is called the total energy radiated from a light-giving source, B the amount of luminous radiation, and C the amount of obscure radiation, then $A = B + C$ and the ratio $\frac{B}{A}$ is the *optical*, or *luminous*, *efficiency* of the light-giving source, because it is the ratio of the radiation that is useful in producing light to the total radiation.

The luminous efficiency of carbon incandescent lamps is less than 3 per cent. and that of the most efficient tube lamps is approximately 10 per cent.

The term *luminous efficiency* must not be confused with *specific consumption*, which is often referred to as the efficiency of an incandescent lamp and which is defined later.

7. Candlepower.—In order to compare intensities of light from different sources, some standard is necessary. The first of these standards of light consisted of a spermaceti candle of standard dimensions burning at a certain rate. This was known as a *standard candle*, and its light was said to have an intensity of one *candlepower*. The candlepower thus became the name of the unit by which the intensity of light from a lamp is measured; thus, a 16-candlepower lamp is one that produces an intensity of light equal to that from sixteen standard candles. For the sake of brevity, the word *candle* is sometimes used in place of candlepower.

Owing to the shape of the filaments, the greatest part of the light from most incandescent lamps is given off sidewise, or horizontally, assuming the lamps to be supported vertically. The light from a lamp will have different candlepowers in different horizontal directions, and the average of these is called the *mean horizontal candlepower* of the lamp. When referring herein to the candlepower of an incandescent lamp, the mean horizontal candlepower is meant, unless otherwise specified.

8. Candle Hour.—From the unit candlepower is derived another unit, called the *candle hour*, which is used as a measure of the period of usefulness, or *life*, of an incandescent lamp and which is, indirectly, a measure of its luminous radiation.

Candle hours are found by multiplying together candlepower and hours; thus in 700 hours, a 16-candlepower lamp gives $16 \times 700 = 11,200$ candle hours, and a 32-candlepower lamp gives $32 \times 700 = 22,400$ candle hours.

9. Nominal Watts.—The size of an incandescent lamp may be specified by giving its candlepower; but the method of rating commonly used specifies the size in watts. For example, a 25-watt lamp is one that takes approximately 25 watts when burned at the proper voltage. A 25-watt lamp may not take exactly 25 watts; hence, this is said to be the *nominal rating* or the *nominal watts* are 25.

INCANDESCENT LAMPS

CLASSIFICATION

10. There are in general commercial use three types of incandescent lamps, differing essentially only in the materials from which the light is radiated. These are the *carbon-filament*, the *metallized-filament*, and the *metal-filament* lamps, named

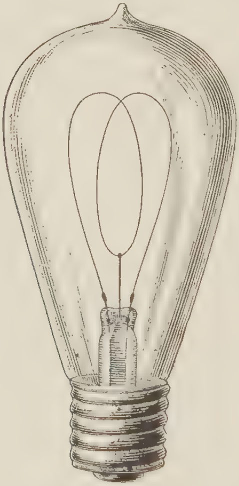


FIG. 1

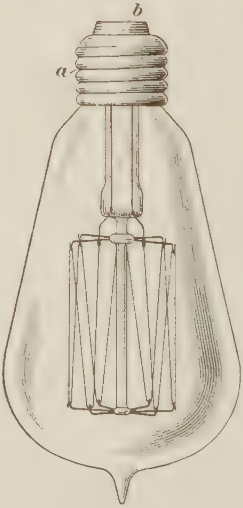


FIG. 2

in the order of their development, though not of their importance.

In Fig. 1 is shown a carbon-filament incandescent lamp, with which nearly every one is familiar. The metallized-filament lamp is similar in general appearances to the carbon lamp. In Fig. 2 is shown a type of metal-filament lamp, having a filament of the metal tungsten. Commercially, carbon-filament lamps are generally known as *carbon lamps* and tungsten-filament lamps as *Mazda lamps*. Some manufacturers refer to metallized-filament lamps by the trade name *Gem*.

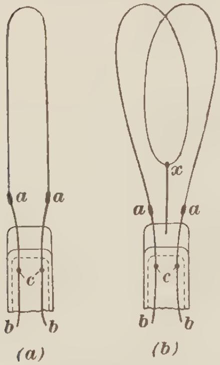
CARBON LAMPS

CONSTRUCTION

11. Squirting Process.—Carbon filaments are today made entirely by the so-called squirting process. The material is a fine grade of cotton that is dissolved usually by a strong, hot solution of zinc chloride. At first a jelly-like substance is produced, but finally the cotton is completely dissolved and the resulting liquid, called *cellulose*, is a heavy syrup. While hot, the solution is filtered to remove impurities and subjected to a vacuum treatment to remove all air and gas. When cold it is forced through a platinum die by air pressure, emerging as a thread into a jar of wood alcohol, which coagulates the thread. The jar revolves very slowly, causing the fiber to lie in coils so that it is readily handled. This process is called *squirting*.

When the jar is full, the thread is allowed to stand several hours and is then removed and washed thoroughly in water to remove the zinc chloride. After washing, the thread is wound on drums about 4 feet in diameter, and dried. In drying, the thread shrinks greatly; for instance, a thread squirted through a .023-inch die shrinks to about .008 inch when dry. The dry cellulose thread is then wrapped on carbon forms and embedded in charcoal or graphite, after which it is heated to a high temperature. Heating converts the cellulose into carbon, producing the carbonized filament. During this process the filament shrinks still more; the one previously mentioned reduces to about .0035 inch.

12. **Flashing.**—After carbonization, the filaments vary somewhat in size and are therefore sorted into lots of like diameters before they are *treated*, or *flashed*, as follows: The filaments are cut to the proper length and then fastened by suitable clamps in a receptacle filled with gasoline vapor. Sufficient current is allowed to pass through the filament to cause it to glow. The heat decomposes the vapor into some of its elements, of which carbon is one, and causes carbon to be deposited on the filament in a form similar to graphite. This deposit greatly reduces the resistance of the filament and also increases the mechanical strength. When the proper resistance is secured, the current is automatically cut off, thus securing uniformity of resistance. The flashing is done mainly to strengthen the filament and to improve the efficiency, for the outer coating of deposited carbon does not radiate heat so rapidly as the original carbon.



(a) (b)

FIG. 3

13. **Size of Filament.**—The size of the filament depends entirely on the candlepower of the lamp and the voltage of the circuit on which it is to be used. The lamp shown in Fig. 1 gives 16 candlepower on a 110-volt circuit. Such a lamp requires about ½ ampere to deliver 16 candlepower; hence, its hot resistance must be approximately 220 ohms. This requires a filament of small diameter and of considerable length. Lamps for lower voltage and larger currents would have shorter and thicker filaments.

14. **Leading-In Wires.**—In Fig. 3 are shown two methods of mounting the filament. It is fastened at points *a* to short platinum wires, called *leading-in wires*, sealed in a glass stem, thus making an air-tight joint. The filament is soldered, or fused, to the leading-in wires with graphite cement, which

enlarges the joints and thus reduces the heating at this point, keeping the leading-in wires themselves cool.

The leading-in wires are made of platinum because this metal expands and contracts with changes of temperature almost exactly at the same rate as glass, and because it does not oxidize, or rust. Since the platinum is sealed into the glass, it would crack the glass if it expanded faster than glass, and if it expanded slower, it would draw away from the glass; either action would cause a leak, the vacuum would soon be destroyed, and the filament would burn out. The platinum wires are very short, extending to points *c* just far enough beyond the actual seal to allow the filament to be cemented on at one end and the copper wires *b* leading to the base at the other end. In Fig. 3 (*b*) the filament is shown fastened at *x* to an *anchor wire*, giving additional strength of support.

15. Bulbs.—Lamp bulbs are made in a variety of shapes, but the most common shape is shown in Fig. 1. This bulb is molded so that it is extremely uniform in size and shape. Filaments of different candlepower require bulbs of different size to radiate the heat properly and prevent undue rise of temperature.

The molded bulb is *tubulated* by heating simultaneously a small spot at the end of the bulb and a small tube and then fusing, or melting, them together, making an air-tight joint. An opening is made from the tube to the bulb while hot by blowing through the tube. The stem with the filament attached is then sealed into the other end of the bulb with an air-tight joint.

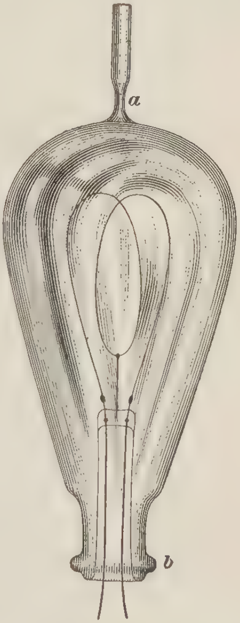


FIG. 4

16. Exhaustion.—A tubulated lamp with the stem and the filament sealed in and ready for exhausting is shown in Fig. 4. The inside of the stem is painted with a red phosphorous paint, which is later vaporized to render the last traces of air inactive. The lamps are then heated in a gas oven to almost the melting point of the bulb, after which they are removed from the oven and connected through the tubes and rubber joints to a vacuum pipe line. A preliminary vacuum is obtained by connecting the pipe line to a good vacuum pump, and when as much air as possible has been removed, the pipe line is connected to an oil-sealed rotary vacuum pump, which removes the remaining free gases. There still remains some gas in the filament and the joints; this is removed by burning the lamp first on 90 per cent. normal voltage and then on about 135 per cent. normal voltage until the joints are white and the lamp is filled with a purplish glow. The valves are then closed, cutting off all connection to the pumps, and the stem is heated with a gas flame, causing the phosphorous to vaporize and to unite with what gas is still left in the bulb and form a solid so small as to be hardly perceptible. Immediately, the purplish glow, which has been caused by electric conduction through the gases, disappears, and the vacuum space takes on its usual invisible appearance.

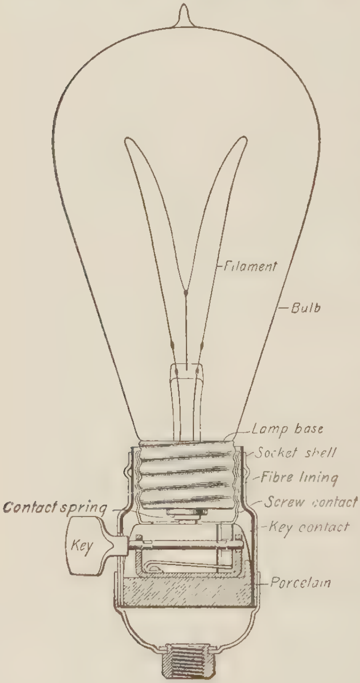


Fig. 5

The lamp is then *sealed off* by heating the contraction *a* in the tube, Fig. 4, and drawing the remainder away. The vacuum is tested by placing the leading-in wires of the lamp to be tested in contact with one terminal of an induction coil and the leading-in wires of a lamp of known poor vacuum on the other terminal. The inspector then holds one lamp in each hand, thus forming a condenser circuit through his body. If the vacuum is perfect, no glow will appear in the lamp under test, but if the vacuum is poor a bluish glow will show.

17. Bases.—After the lamp has been exhausted, it is tested to determine the exact voltage for which it is adapted and is then fitted with a base, which provides a ready means of connecting the lamp to the circuit. The bases are ordinarily made of brass and a waterproof cement. The flange *b* of the bulb, Fig. 4, is so shaped that the cement holds the base firmly in position. The leading-in wires are then soldered to the base and the lamp is complete.

Practically all incandescent lamps have bases of the form shown in Fig. 2, called *screw bases*, or *Edison bases*. One leading-in wire is attached to the outer brass shell *a*, which is provided with a large screw thread, and the other to the projecting center piece *b*, the two pieces *a* and *b* being separated by the insulating cement. When the lamp is screwed into the socket, the screw shell makes one connection and the center piece the other. A lamp screwed into an ordinary screw key socket is shown in Fig. 5, the socket being represented in section.

CHARACTERISTICS

18. Temperature.—The temperature of the filament of a carbon lamp may vary from about 1,600° to 1,950° C. The higher the temperature, the greater will be the light given off by a filament and also the greater will be the light per watt consumed in producing the light. As far as power consumption is concerned, operation at a high temperature is evidently an advantage, but the higher the temperature the shorter will be the life of the lamp. Instead of stating the temperature at which lamps operate, manufacturers find it better to refer to power consumed per candlepower of light produced.

19. Efficiency.—The efficiency, or *specific consumption*, of an incandescent lamp is ordinarily expressed as the watts per candlepower; thus, a carbon lamp giving 16 mean horizontal candlepower and consuming 48 watts requires 3 watts per candlepower. The smaller the specific consumption, the more economical will be the lamp.

It is possible to burn the same lamp at different temperatures, which means at different efficiencies and candlepowers and with different lengths of life. It is apparent that if an increased efficiency is obtained it must be at the expense of length of service, or life; the higher the efficiency, the shorter will be the life. When the cost of power is high, high efficiencies and relatively short life are justified; while if the cost of power is low, lower efficiencies and longer life will give greater economy. Voltage regulation also affects the life of a lamp; efficiency that gives satisfactory life on a circuit where the voltage does not rise more than 2 or 3 volts above normal would not give satisfactory life where the voltage rises 4 or 5 volts above normal. It is therefore desirable that lamps be available in different efficiencies to meet different service conditions. The three standard efficiencies, *high*, *medium*, and *low*, for carbon lamps are 2.97, 3.18, and 3.39 watts per mean horizontal candlepower, respectively. These values apply to all carbon lamps ordinarily used for house lighting, except the smallest sizes, which are of necessity less efficient.

20. Voltage.—An incandescent lamp gives its rated candlepower when its rated voltage is applied to its terminals. Most carbon lamps are made for voltages between the limits of 100 and 130 volts. Eighty-volt lamps have been used considerably for various work, but are being abandoned. Many lamps, however, are made for 200 to 260 volts, although these form a small proportion of the whole. Carbon lamps for voltages below 80 were also used formerly, but these have been almost entirely replaced by metal-filament lamps.

It has been found that a change of the voltage applied to a lamp very materially alters the candlepower and the life of the lamp. Increasing the voltage increases the candlepower and shortens the life; decreasing the voltage decreases the candlepower and increases the life. A small percentage change in the voltage applied to a carbon lamp causes a very much larger change in the life.

In manufacturing carbon lamps, it is impossible to make them all come out at the intended voltage. Thus in a lot of lamps made for 110 volts some may give rated candlepower at 104 volts and others at 116 volts, the larger number, however, giving rated candlepower at or near 110 volts. This difficulty of manufacturing carbon lamps for an exact voltage makes close rating practically impossible if all stations operate at one voltage. Inasmuch as most stations operate at 110 volts, the few operating at odd voltages a little above or a little below 110 can usually obtain closer selection than can be given for 110 volts.

21. Three-Voltage Rating.—This same consideration of non-uniformity in manufacture has caused a change in the method of rating certain types of lamps. Where formerly it was customary to mark, or label, lamps for a single voltage as 110, 106, etc., it has been found preferable to mark them with three voltages as 112, 110, 108, or any similar three voltages 2 volts apart. These marked voltages are known either as the *top*, *middle*, and *bottom* voltages or as the *high*, *medium*, and *low* voltages. The top voltage will give the correct candlepower at the rated voltage, and the lower voltages will give lower operating efficiencies. In a standard 50-watt carbon lamp rated at 112, 110, 108, the top voltage would cause a consumption of 50 watts, which would give 16.8 candlepower, or high operating efficiency of 2.97 watts per candle. The middle voltage would cause a consumption of 48.2 watts, which would give 15.2 candlepower, or medium operating efficiency of 3.18 watts per candle. The bottom voltage would cause a consumption of 46.4 watts, which would give 13.7 candlepower, or low operating efficiency of 3.39 watts per candle.

22. Life.—The **ultimate, or total, life** of an incandescent lamp is the number of hours the lamp will burn before the filament breaks or some other defect occurs to prevent further operation. This life in carbon lamps may be from 500 hours to several thousand in extreme cases.

The candlepower of a given lamp does not remain the same throughout its life, but increases somewhat for a short period and then gradually decreases. At the same time, the current required by the lamp also decreases somewhat, though less rapidly than the light. Hence, the efficiency of the lamp constantly decreases until from a 3-watt lamp when new it may easily become a 5- or 6-watt lamp. Operating incandescent lamps too long is therefore not economical.

The **useful life** of a lamp is the number of hours the lamp will operate economically, and may be much less than the total life.

The **smashing point** denotes the time when the lamps have so decreased in light that it is more economical to break them and replace them with new ones than to continue to burn them. The smashing point varies with the efficiency, and is generally claimed to be reached when the candlepower on rated voltage has dropped to 80 per cent. of its rated value. The cost of carbon lamps is so low that it is advantageous to operate them at such efficiencies that they burn out when the smashing point is reached. These efficiencies are those of the top voltage. The time taken by a lamp to reach its smashing point at this voltage is its useful life, and the two terms are often used interchangeably.

The falling off in candlepower of a carbon lamp during its life is generally attributed to a gradual disintegration, or breaking up, of the filament. This slow throwing off of small particles from the filament increases the resistance and therefore decreases the current and the light. Moreover, the particles of carbon are deposited on the inside of the globe; hence, they blacken it and still further reduce the light given off by the lamp.

23. General Remarks.—Although carbon incandescent lamps are fast being superseded, they are still manufactured for a wide range of voltages and candlepower. The power consumption per candlepower also varies widely. High efficiency carbon lamps generally have short life unless the regulation is very good; hence, such lamps should not be used where the regulation is poor. Carbon lamps are made in the sizes shown in Table I. The 10-watt and 20-watt, 100- to 130-volt lamps and the three 200- to 260-volt lamps are rated on the single-voltage basis only.

TABLE I

CARBON LAMPS

Nominal Watts	Efficiency Step	Actual Watts	Candlepower	Watts per Candlepower	Total Life Hours
		100 to 130 Volts			
10		10.0	2.0	5.00	2,000
20		20.0	4.8	4.15	2,000
25	High	25.0	8.1	3.10	500
	Medium	24.1	7.3	3.31	725
	Low	23.2	6.6	3.52	1,050
30	High	30.0	9.3	3.23	1,050
	Medium	28.9	8.4	3.46	1,500
	Low	27.8	7.5	3.69	2,100
50	High	50.0	16.8	2.97	700
	Medium	48.2	15.2	3.18	1,000
	Low	46.4	13.7	3.39	1,500
60	High	60.0	20.2	2.97	700
	Medium	57.9	18.3	3.18	1,000
	Low	55.7	16.4	3.39	1,500
100	High	100.0	33.6	2.97	600
	Medium	96.4	30.5	3.18	850
	Low	92.9	27.4	3.39	1,350
120	High	120.0	40.4	2.97	600
	Medium	115.8	36.5	3.18	850
	Low	111.4	32.8	3.39	1,350
		200 to 260 Volts			
35		35.0	8.0	4.40	1,000
60		60.0	16.3	3.69	750
120		120.0	32.5	3.69	750

METALLIZED-FILAMENT LAMPS

CONSTRUCTION

24. Metallized-filament lamps are similar to carbon lamps except that before the flashing process metallized filaments are packed in a cylindrical carbon box, which is fed into the end of a carbon tube buried in powdered carbon. A large electric current is set up in the walls of the tube, raising the temperature inside to between 3,000° and 3,700° C. This high temperature reduces the diameter and also the resistance of the filament, changing it wholly or in part to pure graphite. After cooling, the filaments are flashed, as with the ordinary carbon filament, after which they are again placed in the carbon-tube furnace and again fired. During this second heating a decided change occurs in the coating that has been deposited on the filament during the flashing process. This shell has a lustrous steel-gray appearance, and when cold the filament has a resistance of only about 28 per cent. of that which it had before the second firing and after the flashing. The resistance of the core seems to be unaltered, the change occurring only in the coating.

A still more remarkable change is made in the temperature-resistance coefficient of the filament, or, strictly, of the coating. In the original filament, this coefficient is negative, that is, the resistance decreases with increased temperature, while in the metallized filament the temperature-resistance coefficient is positive, like that of metals. These characteristics of the filament are so much like metals that the name *metallized filament* has been applied.

CHARACTERISTICS

25. Efficiency.—Metallized-filament lamps are more efficient than the older carbon lamps. The efficiencies range from 2.81 watts per candle, the low operating efficiency, to 2.50 watts per candle, the high operating efficiency. In operating 700 hours at the high operating efficiency, a 50-watt metallized-filament lamp giving 20 candlepower requires 50×700 = 35,000 watt-hours, or 35 kilowatt-hours, and a 60-watt carbon-filament lamp also giving 20 candlepower requires 60×700 = 42,000 watt-hours, or 42 kilowatt-hours. At 1 cent per kilowatt-hour, the metallized-filament lamp would save 7 cents in the cost of energy for practically the same amount of light, as the candlepower variations during burning are very nearly identical. At the usual commercial prices for energy, the saving would be proportionately higher.

26. Voltage.—The positive temperature coefficient renders metallized-filament lamps more suitable for use on circuits with poor voltage regulation than are carbon lamps. The increase of the metallized-filament resistance with increased temperature tends to keep the current and candlepower more nearly constant. For example, 1 per cent. change in voltage causes about 4.8 per cent. change in candlepower in a metallized-filament lamp and 5.6 per cent. change in a carbon lamp. Better, more uniform light and longer useful life are therefore obtained with the newer lamps on circuits where the voltage regulation is poor.

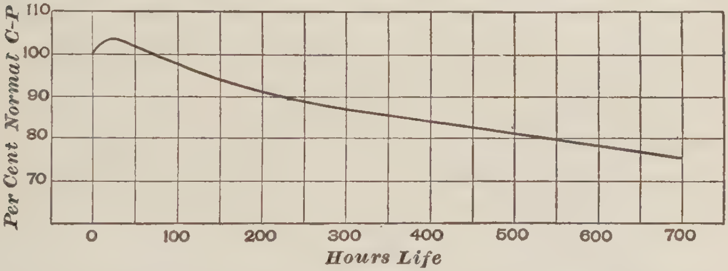


FIG. 6

27. Life.—The life of a metallized-filament lamp may be taken as 700 hours when operated at high efficiency and as about 1,500 hours when operating at low efficiency. The candlepower-life performance curve of a standard lamp operating at high efficiency is shown in Fig. 6. The candlepower of the lamp increases about 4 per cent. in the first 20 hours and then gradually drops off, so that at the end of 70 to 75 hours it is equal to the original candlepower, and at 550 hours has dropped to 80 per cent. and at 700 hours to about 75 per cent.

TABLE II

METALLIZED-FILAMENT LAMPS, 100-130 VOLTS

Nominal Watts	Efficiency Step	Actual Watts	Mean Horizontal Candle-power	Watts per Candle-power	Life Hours
30	High	30.0	10.0	3.00	1,050
	Medium	28.9	9.1	3.18	1,500
	Low	27.9	8.3	3.36	2,150
40	High	40.0	15.6	2.56	600
	Medium	38.7	14.2	2.71	900
	Low	37.3	12.9	2.89	1,300
50	High	50.0	20.0	2.50	700
	Medium	48.4	18.3	2.65	1,000
	Low	46.7	16.6	2.81	1,500
60	High	60.0	24.0	2.50	700
	Medium	58.0	21.0	2.65	1,000
	Low	56.0	19.9	2.81	1,500
80	High	80.0	32.5	2.46	700
	Medium	77.4	29.8	2.60	1,000
	Low	74.6	26.8	2.78	1,500

Table II shows some of the operating characteristics of several metallized-filament lamps for 100 to 130 volts.

TANTALUM LAMPS

28. Many attempts have been made to utilize metals in incandescent lamps. Osmium, a very rare metal, was used in Europe very successfully in laboratory experiments, but it never became a commercial success largely because of its rarity. Tantalum, a comparatively rare metal, has been used commercially somewhat extensively, but is being displaced quite rapidly by the more satisfactory tungsten lamps.

29. The tantalum lamp is shown in Fig. 7. In appearance it is very different from the carbon lamp because tantalum has comparatively low resistivity and the filament must therefore be much longer than a carbon filament of equal resistance and cross-section. The long filament is looped back and forth on the wire supports, or anchors, projecting from the glass rod in the center of the lamp. Tantalum lamps operate at about 2 watts per candlepower for about the same useful life as the carbon or metallized-filament lamp. Tantalum lamps, however, are peculiar in that alternating current causes the filament to become fragile and break more quickly than does direct current.

A characteristic common to most metallic lamps is the ability of the filament to weld after a breakage when the broken parts touch any part of the filament in such a way as to complete the circuit. The current then heats the point of contact sufficiently to weld the two wires together. More or less of the filament will be cut out of the circuit and the resistance lowered, so that the lamp will use more power and give more light, but the life will be shortened more or less according to the amount of the filament that has been cut out.

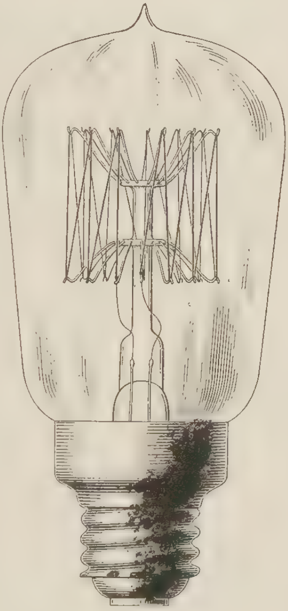


FIG. 7

TUNGSTEN LAMPS

CONSTRUCTION

30. Making the Filaments.—Tungsten is one of the rare metals, though more abundant than either osmium or tantalum. It is steel gray to black in color, depending on the method of manufacture and the amount of impurities present. It is very heavy, having a specific gravity of 18.7 to 20.2, according to the method of manufacture. Tungsten is never found pure in its native state, but usually as a crystalline chemical formation in connection with other metals, also not in the metallic state. The ores are crushed, concentrated, and treated chemically to produce a dirty yellow powder called *tungstic acid*. This is only about 90 per cent. pure when the lamp manufacturer receives it. By complicated, and at present secret, chemical reactions, the tungstic acid is refined and altered until pure metallic tungsten is obtained in a very finely powdered form.

This powdered tungsten is formed into lamp filaments by one of two processes. In the first process, the powdered tungsten is mixed with a suitable binding material and the mixture is squirted, as in the manufacture of carbon filaments. The binding material is then burned out electrically, and the pure metallic tungsten is left in the form of a continuous straight wire. In the second process, which has superseded the first process, the powdered tungsten is compressed by means of powerful hydraulic presses into sticks about $\frac{1}{4}$ inch square by 6 inches long. The sticks are then made strong enough to handle by firing them in an atmosphere of hydrogen in an electric furnace, the hydrogen being necessary to prevent oxidation of the tungsten. The sticks are next placed in copper vessels containing hydrogen and brought to a white heat by the passage of a heavy current; each stick is thereby sintered into a slug of coherent metal. By hot mechanical working through numerous operations in special machines, the slugs are reduced to rods about .03 inch in diameter. Further reductions are accomplished by hot-drawing through a series of diamond dies. Filaments made by this process are called *wire-drawn filaments*.

31. Mounting Tungsten Filaments.—The tungsten filament has a lower specific resistance than the carbon filament and is therefore not only smaller in diameter, but longer, when designed for the same voltage; special mounting is therefore required to avoid excessive breakage from mechanical shocks. For this purpose there is provided in the axis of the lamp a glass rod carrying two sets of anchor wires with hook-shaped ends over which the filament is loosely looped. The only supports to which the filament is firmly fastened are the leading-in wires, Fig. 2; thus, considerable freedom of motion is permitted in the filament and the effects of mechanical shocks and vibrations are reduced. The anchor wires are insulated from each other by the glass rod into which they are fused; otherwise, the filament would be short-circuited. Tungsten lamps are almost as rugged as carbon lamps and have, in fact, been used with entire satisfaction in street-car service.

32. Size of Filaments.—Tungsten filaments vary in length and diameter according to the voltages and candlepowers of the lamps for which they are intended. Except in very large lamps, tungsten filaments are considerably smaller in diameter than the finest carbon filament. Filaments for 15-watt, 110-volt lamps are only .0008 to .0009 inch in diameter, which is finer than a human hair.

33. Leading-In Wires.—Each leading-in wire in a tungsten lamp consists of a piece of platinum wire between two other wires made of copper, nickel, or molybdenum. The platinum is fused into the glass, and the copper wires inside the lamp are led down to the points where the filament is attached. The end of the leading-in wire is rolled out and then bent around to form almost a complete circle, thus having the effect of a hollow end. The end of the filament is inserted in this opening, and the leading-in wire is firmly pressed about the filament, forming a mechanical weld, or joint, known as a *sheath joint.* The joint is usually crimped, and this gives a slight spring effect and perhaps helps to absorb mechanical shocks.

CHARACTERISTICS

34. Temperature.—Because of its very high melting point, 2,800° to 3,000° C., a tungsten filament is operated at higher temperatures than any other; consequently, it gives a greater amount of light for the same power consumption. Also, the light from a tungsten filament is more nearly white, resembling daylight, than that from any other filament.

35. Overshooting.—The tungsten filament has a positive temperature coefficient of resistivity, the resistance increasing so rapidly with increased temperature that the hot resistance is from eleven to thirteen times as great as the cold resistance. Because of this low cold resistance, a relatively large current passes when the lamp is first connected to the circuit, but it quickly reaches the normal amount when the filament becomes heated. The difference between the metal and the carbon filament is very marked in this respect, as may be very readily noted by connecting a lamp of each type to be operated from the same switch. The tungsten lamp will have reached full brilliancy so much ahead of the carbon lamp that the latter will appear distinctly slow in lighting. This quick action has caused considerable discussion regarding the *overshooting* of the lamp; that is, whether the lamp for a very short interval of time during the first heavy rush of current gives more light than when the current has dropped to normal. Recent experiments, however, have established that there is no lag in the resistance of the conductor as would be necessary if this actually happened and that the lamp does not overshoot, but that the action is purely a physiological one due to the action of the human eye.

36. Efficiency.—Tungsten lamps require about one-third as much power as carbon lamps, and less than one-half as much as metallized-filament lamps. In lamps consuming from

25 to 500 watts, operating efficiency ranges from 1.14 watts to .9 watt per candlepower.

37. Voltage-Resistance Curves.—The tungsten lamp is well adapted to circuits with poor voltage regulation, because a given percentage change in voltage causes a smaller percentage change in the power consumption of a tungsten lamp than with other types. The effect of change in voltage on the resistances of different kinds of filaments is shown in Fig. 8. At normal voltage (100 per cent.), the tungsten filament has 1,225 per cent., or 12.25 times, its cold resistance, while the carbon filament has but 50 per cent., or one-half, its cold resistance, showing very plainly the positive and negative temperature coefficients of the respective materials. The small percentage change in power consumption of the tungsten filament with change in voltage is due to the rapid change in resistance owing to the high temperature coefficient. The current in a tungsten filament changes in a smaller ratio than the voltage.

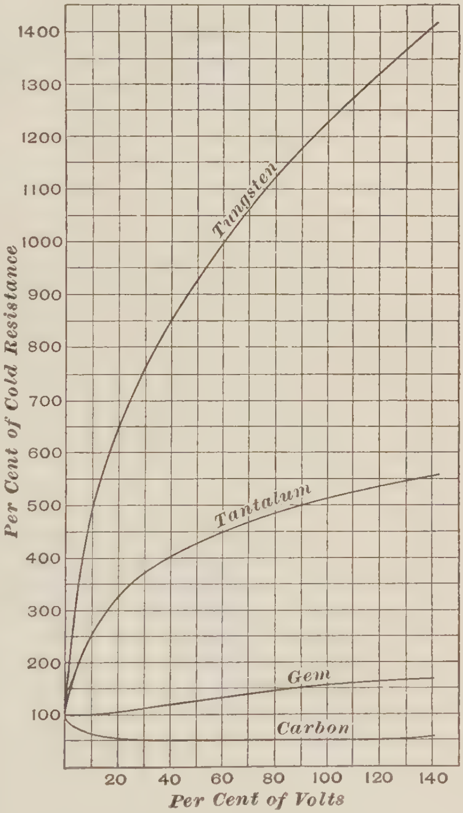


FIG. 8

38. Characteristic Curves.—The variations in candlepower, current, total watts, and watts per candlepower with variation in voltage of a drawn-wire tungsten filament are shown in Fig. 9. The candlepower, the current, and the total watts increase slightly with an increase in voltage, and the watts per candlepower decrease. In other words, the higher

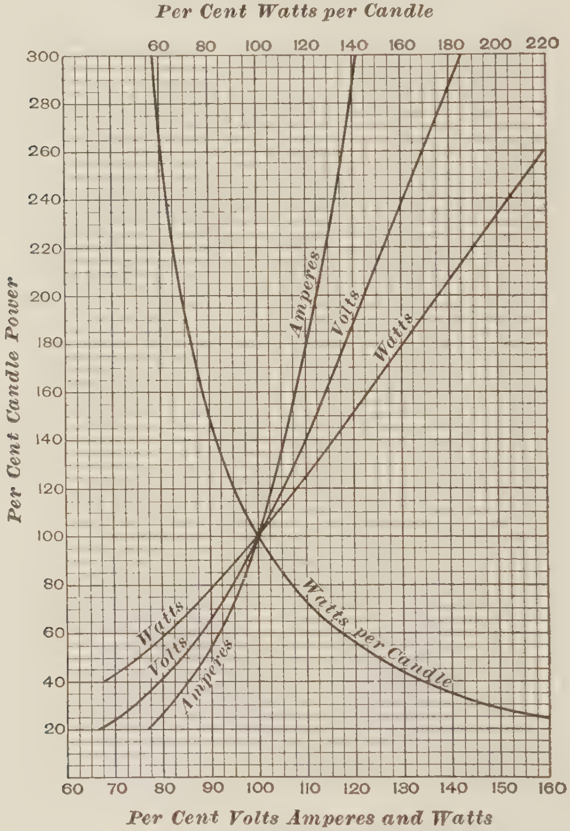


FIG. 9

the voltage, the higher will be the current, the candlepower, and the total watts, and the lower will be the watts per candle.

In obtaining values from Fig. 9, it is necessary to go to the *Volts* curve first. For example, assume that it is desired to ascertain the conditions at 105 per cent. of normal voltage. The vertical line beginning midway between *100* and *110* at the bottom of the diagram is followed until it intersects the *Volts* curve. Then, by following to the left along the horizontal line from the point of intersection, the per cent. candlepower, *120*, is obtained. The same horizontal line intersects the *Watts-per-Candle* curve at a point coinciding with the intersection of this curve with the vertical line through *90* at the top of the diagram, giving the per cent. watts per candle. In a similar manner, by following the horizontal line from the *Volts* curve to the intersections with the *Amperes* and *Watts* curves, and then proceeding vertically to the bottom of the diagram, the per cent. amperes and the per cent. watts are found to be 103 and 108, respectively.

39. Life.—The life of a tungsten lamp is longer than that of any other incandescent lamp, the majority of the ratings giving 1,000 hours. The candlepower decreases with life more slowly in tungsten lamps than in carbon lamps, and the useful life of a tungsten lamp is practically its ultimate life. In Fig. 10 is shown the candlepower-life curve of a standard tungsten lamp operating at normal voltage. It is very similar in shape to that of the carbon lamp, but differs very materially in the slower rate at which the candlepower decreases. In the first 75 hours the candlepower increases to a maximum of approximately 2 per cent. above normal, after which it slowly decreases until at the end of 1,000 hours it has dropped to about only 85 per cent., whereas in the carbon lamp, in 700 hours, the candlepower has dropped to 75 per cent.

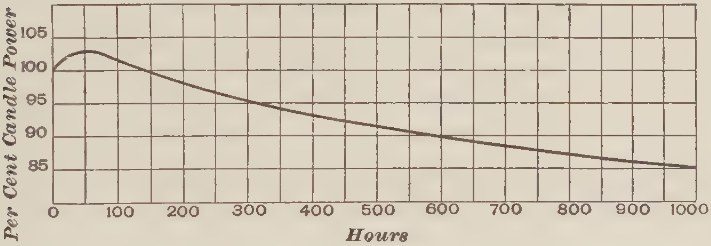


FIG. 10

40. General Remarks.—Tungsten lamps are sold under various trade names, as, for instance, *Osram* and *Mazda*, but these are for advertising purposes only and have no bearing on the lamp construction.

The tungsten lamp can be operated in any position, although for the best light distribution the vertical position should be used. Also, the new drawn-wire tungsten-filament lamps do not require the use of jar, or shock, absorbers, which were sometimes used in places where the pressed-filament lamps were subject to considerable vibration.

Tungsten lamps operate successfully on either direct or alternating current, although the tendency of the filament to crystallize and break is greater on alternating current than on direct.

TABLE III

STANDARD TUNGSTEN LAMPS, 100-130 VOLTS

Watts	Mean Horizontal Candlepower	Watts per Candlepower	Life Hours
10	7.7	1.30	1,500
15	12.0	1.25	1,000
20	17.1	1.17	1,000
25	21.9	1.14	1,000
40	36.4	1.10	1,000
60	56.1	1.07	1,000
100	98.0	1.02	1,000
150	166.7	.90	1,000
250	278.0	.90	1,000
400	444.0	.90	1,000
500	556.0	.90	1,000

The substance resembling hoar frost on the arbor near the anchor wires of smaller lamps and on a special tip at the lower end of the arbor of larger lamps is a chemical that unites with the particles thrown off from the filament as it burns and thus prevents any black deposit on the inside of the bulb. The nature of this chemical is a trade secret; it is known among lamp men as the *vacuum getter*, or simply the *getter*.

Because of the uniformity of tungsten wire, it is possible to manufacture a number of tungsten lamps for a given voltage without the usual variation encountered in the making of carbon lamps. Variations in tungsten lamps of the same size and voltage rating are too small to be detected by a photometer.

41. Tungsten-Lamp Tables.—Tungsten lamps are made for standard multiple service on voltages from 100 to 130 and from 200 to 260. Lamps for special purposes, such as lighting from storage batteries, sign lighting, and automobile lighting are made for various voltages from 6 to 65. Table III lists tungsten lamps for voltages from 100 to 130; lamps for any voltage between these limits are supplied regularly by the manufacturers. Table IV presents lamps for 200 to 260 volts, which are ordinarily made for any voltage divisible by 5 between these limits, as there are few circuits operated at these voltages, and, hence, no great demand for lamps of odd voltages. The lamps listed in Tables III and IV can be obtained in either round bulbs or standard bulbs; they are rated on the single-voltage basis only.

TABLE IV

STANDARD TUNGSTEN LAMPS, 200-260 VOLTS

Watts	Mean Horizontal Candlepower	Watts per Candlepower	Life Hours
25	18.8	1.33	1,000
40	31.3	1.28	1,000
60	48.8	1.23	1,000
100	87.0	1.15	1,000
150	134.0	1.12	1,000
250	227.0	1.10	1,000

No data on tungsten-lamp characteristics can be taken as standard for more than a relatively brief period of time. Manufacturers are continually experimenting to improve the efficiency and to reduce the cost of the tungsten lamp, with the result that lamps made at different times possess different characteristics.

Reliable data on the latest output can always be obtained from the manufacturers or from the National Lamp Works of the General Electric Company, Cleveland, Ohio.

CHOICE OF LAMPS

COST OF LIGHTING

42. The cost of electric lighting by incandescent lamps is made up of two items, the cost of energy consumed and the cost of renewing, or replacing, the lamps. The most economical lamp selection for a given number of candle hours can be determined by calculating the total cost of energy and lamps at the prevailing prices. By assuming large figures to avoid fractional numbers of lamps, say 10,000 candlepower for 10,000 hours, results can be computed as follows: If 50-watt carbon lamps are selected from Table I, the number required for 10,000 candlepower is 10,000÷16.8=595. In 10,000 hours these lamps consume approximately $\frac{595\times50\times10{,}000}{1{,}000}=297{,}500$ kilowatt-hours when operated at high efficiency. The total life of each lamp at this efficiency is 700 hours, and the number

TABLE V

COMPARISON OF ENERGY AND RENEWALS OF INCANDESCENT LAMPS

(10,000 Candlepower, 10,000 Hours)

Type of Lamp	Efficiency Step	Actual Watts	Mean Horizontal Candlepower	Life Hours	No. Lamps 10,000 Candlepower	Kilowatt-Hours in 10,000 Hours	Renewals in 10,000 Hours
Carbon.......	High	50.0	16.8	700	595	297,500	8,500
	Medium	48.2	15.2	1,000	658	317,160	6,580
	Low	46.4	13.7	1,500	730	338,720	4,870
Metallized filament......	High	40.0	15.6	600	641	256,400	10,680
	Medium	38.7	14.2	900	704	272,450	7,820
	Low	37.3	12.9	1,300	775	289,080	5,960
Tungsten......		20.0	17.1	1,000	585	117,000	5,850

of renewals must be $\frac{10,000}{700}\times 595=8,500$. Similar calculations can be made for each operating efficiency for any type and size of lamp and the results arranged as in Table V for as many lamps as are under consideration.

43. The figures in the last three columns of Table V afford a ready means of calculating the total cost of a given amount of light in candle hours with the lamps specified at given prices for lamps and energy. For example, assume that a building requires 1,000 candlepower; that energy can be purchased or generated at 3 cents per kilowatt-hour; and that the prices of the lamps listed in Table V are carbon, 16 cents each, metallized filament 20 cents each, and tungsten 30 cents each. The cost of lighting per 1,000 hours with these lamps will then be as shown in Table VI. If the question of light distribution is ignored, the table shows tungsten lamps to be most economical. When, with different locations, shades, or reflectors, more than one selection of lamps will give the proper light distribution for given conditions, calculations similar to the foregoing will indicate the most economical choice as to type, size, and operating efficiency.

TABLE VI

COMPARISON OF COST OF LIGHTING WITH INCANDESCENT LAMPS

(*1,000 Candlepower, 1,000 Hours. Prices of Energy and Lamps in Art.* **43**.)

Type of Lamp	Efficiency Step	Kilowatt-Hours in 1,000 Hours	Renewals in 1,000 Hours	Cost of Energy in 1,000 Hours	Cost of Renewals	Total Cost per 1,000 Hours
Carbon..........	High	2,975	85.0	$89.25	$13.60	$102.85
	Medium	3,172	65.8	95.16	10.53	105.69
	Low	3,387	48.7	101.61	7.79	109.40
Metallized filament..........	High	2,564	106.8	76.92	21.36	98.28
	Medium	2,725	78.2	81.75	15.64	97.39
	Low	2,891	59.6	86.73	11.92	98.65
Tungsten..........		1,170	58.5	35.10	17.55	52.65

QUALITY OF LIGHT

44. In addition to its economy, the tungsten lamp possesses the advantage of superior quality of light. The light from a carbon filament has an orange color, decidedly in contrast to the brilliant white light from a tungsten filament. The light from a metallized filament is whiter than that from a carbon filament, but does not attain the whiteness of the tungsten light. Tungsten lamps are therefore greatly superior to the other two classes for color matching or for other purposes where light approaching daylight in quality is desirable.

SPECIAL TYPES

SERIES STREET LAMPS

45. General Type.—Incandescent lamps are used for street lighting in suburban districts and parks and in clusters in ornamental lamp posts; they are also used to some extent in the arches with which the main streets of some towns have been provided. The series tungsten lamp is the most important type for this service, owing to its high efficiency and rugged characteristics. This type of lamp is made for relatively large current and low voltage for a given wattage, which permits the use of a strong lamp filament. A 100-candlepower tungsten lamp for series street-lighting service is shown in Fig. 11.

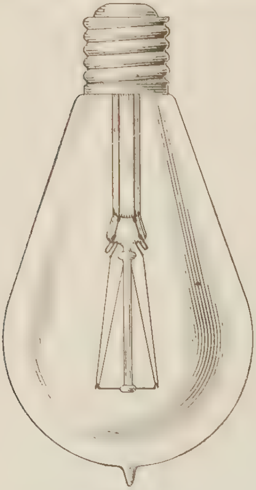


Fig. 11

46. Requirements for Series Service.—In selecting lamps for series service, slight deviations from the voltage and candlepower ratings are of little consequence, provided the current rating is correct. If a 60-candlepower series lamp

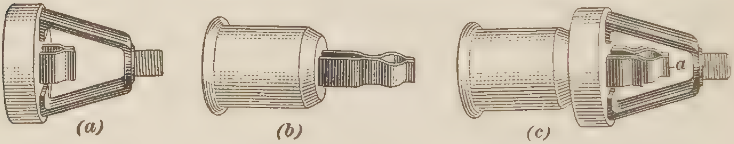
TABLE VII

TUNGSTEN STREET LAMPS

Amperes	Mean Horizontal Candle-power	Average Total Watts	Watts per Candle-power	Average Volts	Life Hours
3.5	32	33.6	1.05	9.6	1,350
	40	41.3	1.03	11.8	
	60	60.6	1.01	17.3	
	80	80.0	1.00	22.9	
4.0	32	34.6	1.08	8.6	1,350
	40	42.0	1.05	10.5	
	60	61.2	1.02	15.3	
	80	80.0	1.00	20.0	
	100	100.0	1.00	25.0	
	200	200.0	1.00	50.0	
	350	350.0	1.00	87.5	
5.5	32	38.1	1.19	6.9	1,350
	40	45.6	1.14	8.3	
	60	63.0	1.05	11.5	
	80	81.6	1.02	14.8	
	100	100.0	1.00	18.2	
	200	200.0	1.00	36.4	
	350	350.0	1.00	63.6	
6.6	32	41.6	1.30	6.3	1,350
	40	48.8	1.22	7.4	
	60	65.4	1.09	9.9	
	80	81.6	1.02	12.4	
	100	100.0	1.00	15.2	
	200	198.0	.99	30.0	
	350	346.5	.99	52.5	
7.5	32	45.0	1.41	6.0	1,350
	40	52.0	1.30	6.9	
	60	67.5	1.13	9.0	
	80	82.5	1.03	11.0	
	200	196.0	.98	26.1	

requiring 3.5 amperes should be included in a circuit of 60-candlepower series lamps requiring 3.6 amperes, the current in the circuit would be too great for this lower amperage lamp and would shorten its useful life. A 3.5-ampere lamp giving 60 candlepower and requiring 20.2 volts would operate with perfect satisfaction in the same circuit with 3.5-ampere lamps giving 61 candlepower and requiring 20.6 volts, because the current in the line would automatically be maintained correct by some type of constant-current generator or regulator.

Characteristics of tungsten series street lamps are shown in Table VII. These lamps will be gradually superseded with the development of the nitrogen-filled lamp described later. In ordering tungsten series lamps, the amperage of the line and the candlepower of the lamps should be specified; whereas, in ordering lamps for multiple service, the voltage and watts are specified, as previously explained



(a) (b) (c)

FIG. 12

47. Series Sockets.—Series street lamps employ special sockets known as *series sockets*. On constant-potential series systems, where no automatic current regulator is employed at the central station, each lamp socket is some form of reactance or resistance, called a *regulator*, that is automatically connected into circuit in case the lamp burns out. This regulator has practically the same effect on the circuit as the lamp itself, not only maintaining the circuit, but also helping to keep the current at its normal value.

Another type of series socket, known as the *film cut-out socket*, is shown in Fig. 12. The receptacle is shown in (*a*) and the socket in (*b*); to assemble them, the metal tongues of the socket are forced between metal spring clamps of the receptacle, where they are held as shown in (*c*). The *cut-out* for this series socket consists of two small metal disks between which is a thin film of shellac or mica. The cut-out is placed at *a*, Fig. 12 (*c*), between the ends of the tongues of the socket and prevents contact between them as long as the film is intact. As soon, however, as the lamp fails, or burns out, the voltage at the terminals of the lamp will momentarily rise until the film of mica or shellac is broken down and current passes through the socket only. This reduces the resistance of the circuit by that of one lamp, but the regulator in the power station quickly brings the current to the normal value.

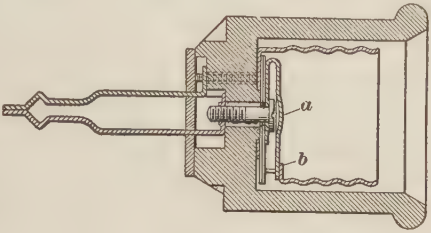


FIG. 13

A cross-section of the film socket is shown in Fig. 13. When a lamp is in place, the spring *a* is held away from the copper shell of the socket; but when the lamp is removed the spring makes contact with the shell at *b*, thus maintaining the circuit, which normally is completed through the lamp filament. The cut-out is not shown in Fig. 13. This type of socket is intended for use on only series circuits with an automatic regulator at the station.

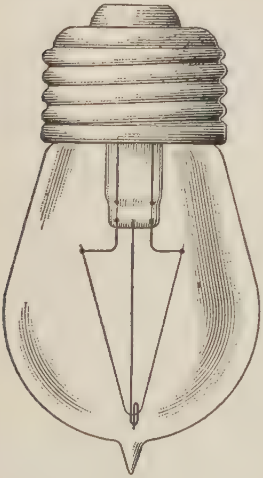


FIG. 14

SIGN LAMPS

48. Lamps of small candlepower have been designed especially for sign lighting. A list of these lamps is given in *Sign Wiring*. The first tungsten lamps made purposely for electric signs were designed in $2\frac{1}{2}$- and 5-watt sizes for voltages ranging from 10 to 13. A 5-watt lamp of this type is shown in Fig. 14. Owing to the necessity of connecting the low-voltage lamps in multiple series or in series multiple on the usual lighting service, they are now being replaced by 5- and 10-watt lamps for voltages ranging from 50 to 65 and from 100 to 130, respectively. These do not differ from the lamp shown in Fig. 2, except that they are smaller in size, giving 3.6 and 7.1 candlepower, respectively, at a specific consumption of 1.4 watts per candle.

Carbon sign lamps, which are now becoming obsolete, are usually made in a 20-watt size, giving approximately 4 candlepower. The average total life of either tungsten or carbon sign lamps is rated at 2,000 hours.

TUNGSTEN LAMPS FOR ELECTRIC-RAILWAY SERVICE

49. Tungsten lamps with filaments made by the old squirting process were unsatisfactory for use in electric-railway service, on account of breakage of the filaments due to vibration. This difficulty has been overcome in the new drawn-wire filament, with the result that electric-railway companies are adopting tungsten lamps for train lighting. These lamps are made for any voltage divisible by 5 from 105 to 130 and in four sizes, a 23-watt lamp operating at 1.3 watts per candle, a 36-watt lamp at 1.26 watts per candle, a 56-watt lamp at 1.16 watts per candle, and a 94-watt lamp at 1.14 watts per candle, each rated at an average total life of 1,500 hours. The lamps are used five in series on circuits ranging in voltage from 525 to 650, and, hence, must be selected for the same amperage, as in the case of series street lamps; otherwise, some lamps in the series will operate at too high efficiency, resulting in diminished life; but, if street-railway lamps for a given voltage are specified in ordering, this feature will be taken care of when the order is filled.

AUTOMOBILE LAMPS

50. A special type of tungsten lamp, designed for the headlights of automobiles, is shown in Fig. 15. Lamps of this type operate on 6 or 7 volts at 1 watt per candlepower. They are made in sizes ranging from 9 to 24 candlepower. The type of filament shown in Fig. 15 is known as a *close-coiled* *filament.* Its object is to make the light source approximate a point, so that when the filament is placed at the approximate focus of a parabolic reflector most of the light rays will be reflected straight ahead. The parabolic reflector is described in another Section in connection with searchlights.

The type of base shown in Fig. 15 is known as the *Ediswan,* or *bayonet, base.* The two lugs fit into slots in the sockets, where they are locked by a slight turn of the lamp. The socket has two small contact plungers held outwards by spiral springs. When the lamp is in place, these plungers make contact with two plates in the bottom of the base, and the springs hold the lugs firmly in the slots, so that the lamp has but little tendency to be jarred loose.

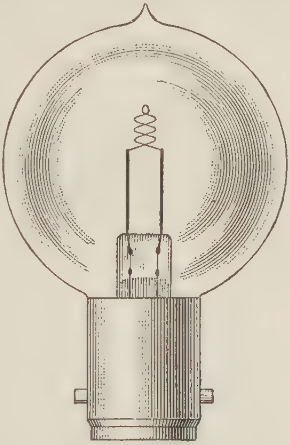


FIG. 15

ILLUMINATION

STANDARDS OF LIGHT

51. The unit of light intensity generally accepted as the standard is the **International candlepower.** Although this unit retains the name candlepower, the standard candle, to which reference has already been made, is no longer used as a primary standard of light.

The international candlepower is defined as one-twentieth of the intensity of light emitted in a direction perpendicular to the surface of 1 square centimeter of molten platinum at its temperature of solidification. This unit is slightly smaller than the old British, or Parlimentary, standard, so that a lamp formerly rated at 16 candlepower now becomes 16.26 candlepower. The molten platinum standard can be used only in laboratories equipped with every possible convenience for its use, but it serves as a final reference, or primary standard. For ordinary purposes, other standards, as here described, are used.

52. The **Carcel lamp** is an Argand (hollow cylindrical flame) burner of specified dimensions fitted with a standard form of glass chimney and consuming, normally, 42 grains of refined colza oil per hour and giving about 9.6 International candlepower. The oil, made from rape seed, is not definite enough in composition to secure entire uniformity, so that the relation between the International candlepower and the Carcel unit cannot be stated more exactly.

53. The **Hefner lamp,** also known as the *amyl-acetate lamp*, is one of the most reliable standards. The lamp burns amyl acetate (sold in alcohol solution as essence of pears) with a wick of standard size, which is adjusted in height until the top of the flame is 40 millimeters from the top of the wick tube. The light has a rose-colored tint, which makes it difficult to use in comparing lights more nearly white. The Hefner unit is smaller than the International candle; 1 Hefner = .9 International candle. If the height of the flame is made 45 millimeters instead of 40, the Hefner is equal to 1 candlepower.

54. Incandescent Lamp Standards.—The incandescent lamp when properly aged by burning for at least 100 hours has practically constant candlepower for a further period of 75 to 100 hours, and forms a thoroughly reliable secondary standard of light intensity. Standardized and certified lamps with special spiral-shaped filaments may be obtained at a reasonable price that permits a central station to maintain a satisfactory standard of light with which its lamps may be compared.

FUNDAMENTAL LAWS

LAW OF INVERSE SQUARES

55. Suppose that a candle is placed at A, Fig. 16, with a screen B at a distance of 2 feet from it. The screen is shown bent to represent part of a spherical surface with the candle at the center. The light passing through an open area $a\,b\,c\,d$ will fall on area $a'\,b'\,c'\,d'$ on a screen in position C, 4 feet from the candle. Since the similar dimensions of the two areas are proportional to the distances of the screens from the candle, area $a'\,b'\,c'\,d'$ is four times area $a\,b\,c\,d$; hence, since the number of rays of light to both surfaces is the same, the illumination on $a'\,b'\,c'\,d'$ is only one-fourth that on $a\,b\,c\,d$. Doubling the distance of the screen from the candle reduced the illumination to one-fourth its former value. From this and similar reasoning may be deduced the **law of inverse squares:**

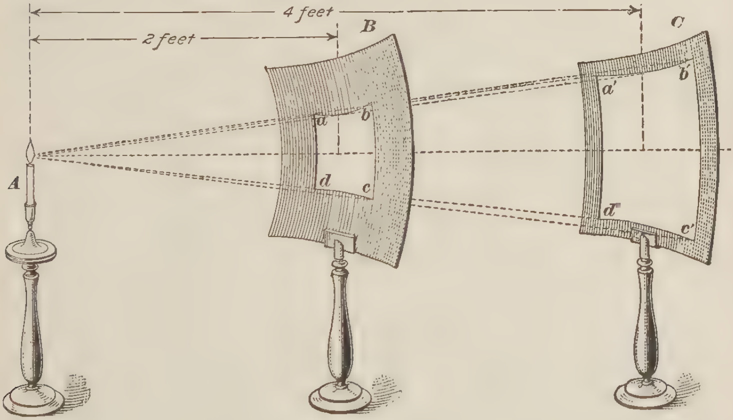


FIG. 16

The illumination, or flux of light per unit area, produced on an object by a source of light so small as to be essentially a point varies inversely as the square of the distance of the object from the source.

This law may be expressed by the formula

$$x = \frac{B}{d^2},$$

in which
x = illumination;
B = intensity of source of light;
d = distance.

If B is in candlepower and d in feet, x will be expressed in terms of a unit called the *foot-candle*, which is the illumination on a surface 1 foot from a light of 1 candlepower.

Where the source of light is materially larger than a point and is distributed over a considerable area, as, for instance, in tube lights, the law of inverse squares is not strictly true, and it becomes impossible to formulate a satisfactory rule unless the light is measured from such a distance that the source has become essentially a point. The rule holds for incandescent and arc lamps.

COSINE LAW

56. Another fundamental law of illumination is the **cosine law:** *The illumination on a plane is proportional to the cosine of the angle that this plane makes with another plane at right angles to the light rays.* In Fig. 17 it is seen that the same number of rays strike plane B as are received by plane A, which is perpendicular to the rays. But B is larger than A; therefore, the illumination on B will be less than that on A, the relative values of illumination varying inversely as the ratio between the areas of the planes. This ratio is equal to the cosine of the angle a between the planes.

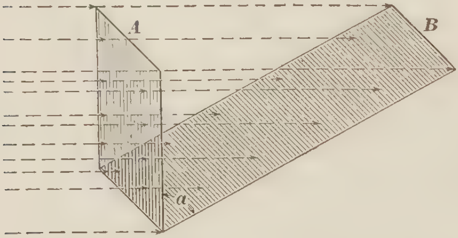


FIG. 17

Let x_1 = illumination on A;
x_2 = illumination on B.

Then, $$x_2 = x_1 \cos a$$

When angle a is known, its cosine can be found from a table of trigonometric functions.

PHOTOMETRY

TYPES OF PHOTOMETERS

57. Elementary Photometer.—A **photometer** is a device for measuring or comparing intensities of light. An elementary form is shown in Fig. 18. The standard candle, or lamp, A and the incandescent lamp B under test, with the screen C and scale S between them, are placed in a dark room, so that one side of the screen may be illuminated by the candle alone and the other side by the lamp alone. By moving the screen, a position can be found where both sides will be equally illuminated. Suppose that such a position has been found and that the distances d_1 and d_2 have been read from scale S. Then, if B_1 is the candlepower of A, and B_2 the candlepower of B, it follows from the law of inverse squares that

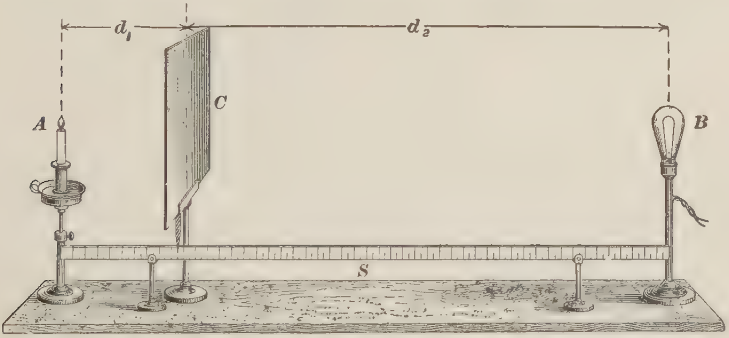


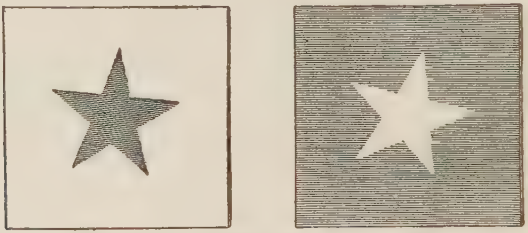
FIG. 18

$$\frac{B_2}{B_1} = \frac{d_2^2}{d_1^2} \qquad (1)$$

and, hence, that

$$B_2 = B_1 \frac{d_2^2}{d_1^2} \qquad (2)$$

58. The Bunsen Screen.—The arrangement of the different parts of the Bunsen photometer is essentially the same as that shown in Fig. 18; the distinguishing feature lies in the style of screen used. In order to overcome the difficulty of telling when a simple screen like that shown in Fig. 18 is illuminated equally on both sides, a screen is made by taking a piece of good quality of white paper, free from glaze, and making a grease spot in its center, as indicated by the star in Fig. 19. If such a screen is held so that the front is more strongly illuminated than the back, the grease spot will appear dark on the white ground of the paper, as shown in (*a*). If the screen is more brightly illuminated on the back, as, for example, if it is held between the eye and a window, the grease spot will appear light on a dark ground, as shown in (*b*). If such a screen is mounted in place of the screen *C* in Fig. 18, the grease spot will disappear almost entirely when the two sides of the screen are equally illuminated. In some types of Bunsen screens, the grease spot will not disappear entirely, owing to the kind of paper used, which fact causes the ungreased part to absorb more or less light than the grease spot. The result is called a *contrast screen*, which shows a condition of balanced illumination where the spot appears the same on the two sides.



(*a*) FIG. 19 (*b*)

59. The Bunsen Sight-Box.—The ability to see both sides of a Bunsen screen simultaneously is an advantage, for any contrast between them is more noticeable than if only one side could be seen at a time. Hence, mirrors and other reflecting devices have been used in what is termed a **sight-box**, which is merely a box in which the screen itself is placed. In Fig. 20 is shown the plan of a Bunsen sight-box with two mirrors *a* and *b* set at equal angles to the screen *c*. The light comes from either side at *d* and *e* and is reflected from the screen *c* to the mirrors and from there to the observer, whose eyes are placed at the opening *f*, and thus both sides of the screen are seen simultaneously.

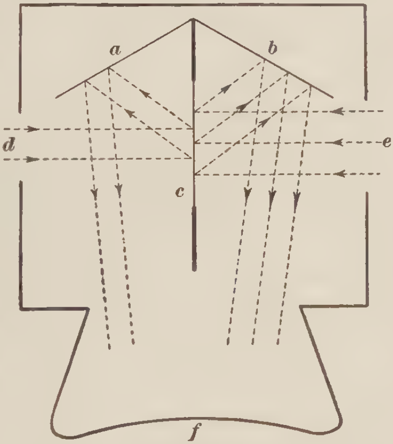


FIG. 20

60. The Lummer-Brodhun Sight-Box.—A plan of a Lummer-Brodhun photometer sight-box is shown in Fig. 21. The light enters at *a* and *b* and is reflected from the sides of the white, opaque screen *c* to the mirrors *d* and *e* and thence to the prisms *f* and *g*. The outside rays from *d* strike the convex face of *f* where it is not in contact with *g* and are reflected within the prism toward *h*, where they are absorbed by the black surface of the sight-box. The center rays entering *f* (but a single one is shown) pass directly through to prism *g* and to opening *i*, where they are seen by the observer. All the rays that strike the prism *f* where it is in contact with *g* pass through, so that if light entered at *a* only the observer at *i* would see a small ellipse of light. The central rays from *e* (two are shown) reach the surface of prism *g* where it is in contact with *f*, and pass through to *h* without being reflected. The outer rays from *e* (two are shown) reach *g* where it is not in contact with *f*, and are reflected to *i*, where they are seen by the observer. If light entered at *b* only, the observer would see an elliptical ring of light. But with light entering at both *a* and *b*, the observer sees an ellipse within a ring as indicated at *a b* in Fig. 22, until the photometer is adjusted so that both sides of screen *c*, Fig. 21, are equally illuminated, when there will be little or no contrast between the ellipse and the ring.

As any difference in the reflecting powers of the two sides of the screen would cause inaccuracy in the setting, it is essential that the average of two readings be taken; one with the sight-box in the position shown, and the other with it reversed so that the light which formerly entered at *a* enters at *b*. The box is pivoted for easy reversal. The use of this sight-box is restricted to the comparison of lights of the same, or nearly the same, color.

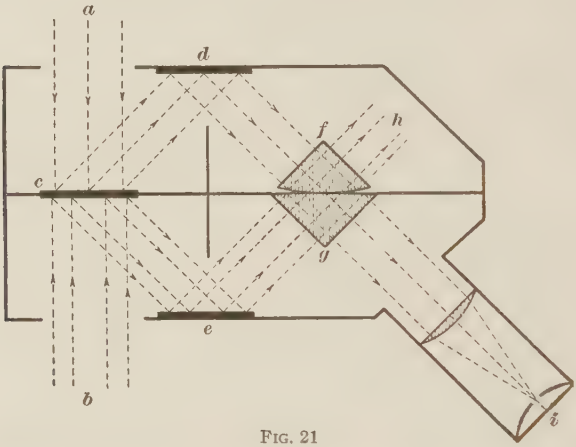


FIG. 21

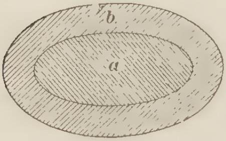


FIG. 22

61. Flicker Photometers.—Flicker photometers are used where the lights to be compared are materially different in color. The screen is arranged so that lights from two sources are presented to the eye in rapid succession. If the lights are of different intensities, there will appear to be a continuous light that flickers. If the lights are of the same intensity, but of different color, a flicker will still appear, due solely to the color. But this color flicker may be eliminated by increasing the speed until the colors blend, so that, if the lights are equal in intensity, all flicker will cease.

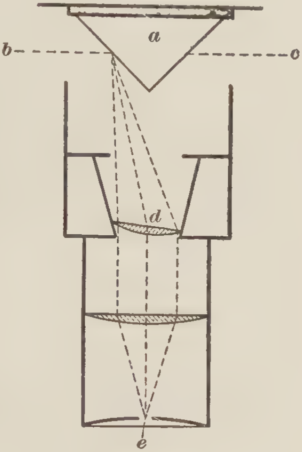


FIG. 23

62. The Schmidt and Haensch flicker screen accomplishes the change from one light source to another by the method shown in Fig. 23. The screen proper is the wedge *a*, of plaster of Paris, which receives light from *b* and *c*. The lens *d* is mounted obliquely in a tube that is free to revolve about an axis *d e*. In the illustration, the lens tilts to the right, focusing on the side of the wedge toward *b*; but when revolved a half turn, it will tilt to the left, focusing on the side of the wedge toward *c*. Thus, as the lens revolves, the observer at *e* sees first one side of the screen, then the other.

PHOTOMETRIC MEASUREMENTS

63. Preliminary Remarks.—To provide ready means of adjusting the position of the photometric screen between the two light sources, the lamps and the screen, or sight-box, are customarily supported on a track, or bar, called a *photometer bar*. This bar is ordinarily about 10 feet long and is marked, usually, into 100 or 1,000 equal parts to permit convenient readings of the position of the screen to be made.

Behind each lamp is placed a dead-black surface, which prevents any reflection along the track either from the lamp itself or from outside sources. Dead-black diaphragms, or shields, are also used between the lamps. These have openings that permit the passage of light from the lamps under test to the screen, but prevent outside light from interfering.

Specially prepared rooms from which all external light can be excluded and in which all the furnishings, as well as the walls and ceiling, are painted dead-black are generally provided for photometric work. Photometers can, however, be used in rooms both where light is admitted and where the walls are not black, though it is less desirable to do so. In such rooms, the dead-black shields behind the lamps and the diaphragms along the track must be so arranged that they cut off from the screen every ray of light from all sources except the lamps under test. The openings of the diaphragm should be graded in size. If the screen can be seen from any position except those directly in the line from the lamps under test to the screen, then the diaphragms are not properly placed.

64. Manipulation.—The photometer is ordinarily used by moving the screen or sight-box continuously in one direction until a balance appears to be obtained, and then moving the screen still further in the same direction until it is obviously out of balance, when it is moved continuously back until a balance is again apparently obtained. The two positions thus found will probably not be the same and the average of the two should be used. If possible, the sight-box should be reversed and a second average reading obtained so as to eliminate any errors that may exist in the photometer itself. The candlepower of the lamp under test is found by formula **2**, Art. **57**.

EXAMPLE.—The bar of a photometer has 100 divisions. At one end of the bar is a Hefner lamp; at the other end is an incandescent lamp of unknown candlepower. A balance is obtained with the screen 19 divisions from the Hefner lamp. What is the candlepower of the incandescent lamp?

SOLUTION.—As the total length of the bar is 100 divisions, the distance of the screen from the incandescent lamp is $100-19=81$ divisions. According to Art. **53**, the Hefner lamp gives .9 c. p. Therefore, according to formula **2**, Art. **57**, the candlepower of the incandescent lamp is

$$B_2 = .9 \times \frac{81^2}{19^2} = 16.4, \text{ nearly. Ans.}$$

65. In practical operating service, an electric incandescent lamp is generally used as a standard, and a balance can be somewhat more easily obtained by varying the voltage applied to the standard lamp than by moving the sight-box. The screen is set in a permanent position midway between the lamps, if they are of approximately the same intensity. The change in the voltage applied to the standard lamp is readily procured by a rheostat. When the condition of balance is found, the voltage applied to the standard lamp is read on a voltmeter; and from the curve of characteristics of the standard lamp the candlepower corresponding to this voltage can be read directly. This will be the candlepower of the lamp being tested, provided the screen is midway between the lamps. If the screen is not midway between the lamps, formula **2,** Art. **57,** must be used.

LIGHT DISTRIBUTION

DISTRIBUTION FROM CARBON LAMPS WITHOUT REFLECTORS

66. Horizontal Distribution.—The term mean horizontal candlepower has been briefly defined in Art. **7.** In Fig. 24 is shown how the candlepower of a carbon lamp varies in different horizontal directions *1*, *2*, *3*, etc. The distance from the center to any point on the irregular curved line surrounding the lamp shows the relative candlepower in that direction. The average of these candlepowers is the mean horizontal candlepower of the lamp.

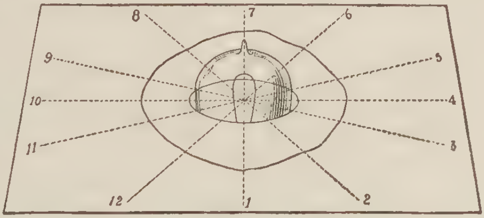


FIG. 24

The mean horizontal candlepower of an incandescent lamp is measured by mounting the lamp vertically in a socket, and then rotating it about its vertical axis at about 180 revolutions per minute while the photometric observations are being made.

67. Vertical Distribution.—In Fig. 25 is shown how the light from a carbon lamp varies in a vertical plane. Viewed from position *1*, the light is almost entirely cut off by the base, and the candlepower is very low. The maximum candlepower is in directions *2* and *4*. Straight through the bottom, direction *3*, the light is below the maximum, because the filament is viewed end on. The directions in which the candlepower will be greatest depends on the shape of the filament of the lamp, but will naturally be in that direction from which the greatest part of the filament can be seen.

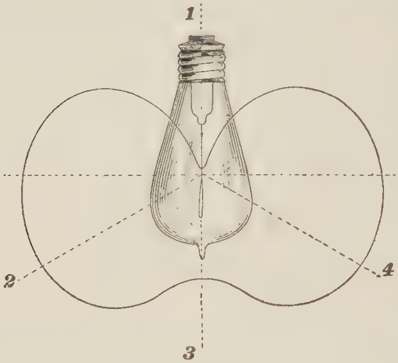


Fig. 25

MEAN SPHERICAL CANDLEPOWER

68. If readings of the candlepower of a lamp are taken in many directions in all planes through the lamp, their average will be the **mean spherical candlepower.** In other words, the mean spherical candlepower represents that intensity of illumination to which the irregular illumination of the lamp would be equivalent if it were uniformly distributed in all directions. The *mean hemispherical candlepower* is the average candlepower over a hemisphere. When a reflector is used over a lamp nearly all the light is thrown downwards, and the mean candlepower for the lower hemisphere is greater than the mean spherical candlepower of the lamp without a reflector.

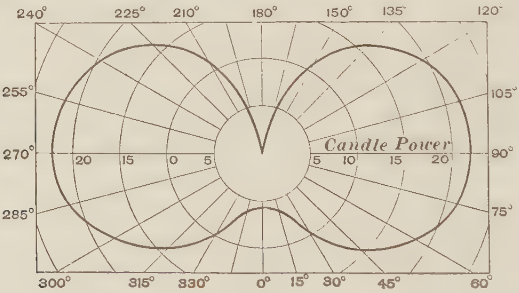


Fig. 26

DISTRIBUTION CURVES FOR TUNGSTEN LAMPS

69. Distribution from Bare Lamp.—The variations in the intensity of the light given by a carbon lamp in different directions are shown in Figs. 24 and 25 for horizontal and vertical planes. These curves also show the manner in which the light from a metallized-carbon lamp is distributed. The tungsten lamp gives a different light distribution owing to the different shape of the filament. The horizontal distribution is so nearly uniform that a curve representing it would be practically a circle.

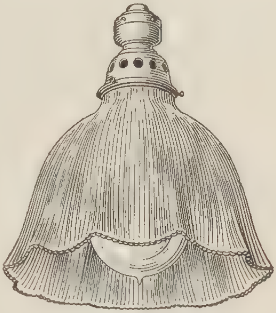


FIG. 27

The vertical distribution curve of a tungsten lamp with base up is shown in Fig. 26. As in Fig. 25, the distance from the center to any point on the heavy line shows the intensity of light in that direction. Directly above the base there is no light and directly below the tip the light decreases to approximately one-third the maximum value at right angles to the filament.

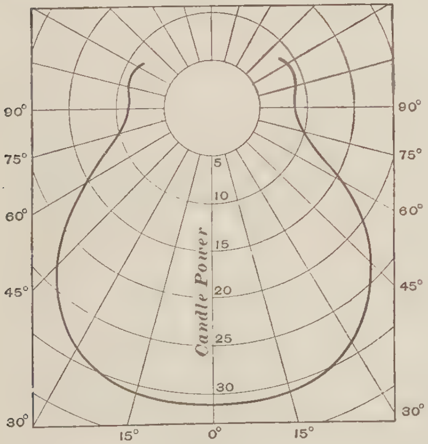


FIG. 28

70. Distribution With Reflectors.—The curves of distribution of light previously mentioned are for the bare lamps without reflectors or shades. By the use of proper reflectors the distribution can be materially altered so as to be more effective. A tungsten lamp in an intensive prismatic reflector is shown in Fig. 27. The distribution curve for such a combination is shown in

Fig. 28. The same lamp was used to obtain the curves in Figs. 26 and 28; but in the latter the light has been reflected from its previous maximum in a horizontal direction to a maximum in a vertical direction.

Fig. 29 shows a tungsten lamp in a focusing-type reflector, which is slightly narrower near the top than the intensive reflector, Fig. 27. Fig. 30 shows the distribution with a focusing reflector to be over a very small angle, scarcely 10° from the vertical.

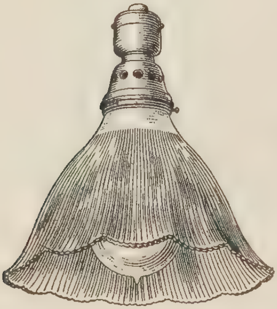


FIG. 29

Fig. 31 shows the light distribution from the same lamp with a reflector of the extensive type, giving maximum intensity at an angle of approximately 40° from the vertical. The general appearance of the extensive reflector very closely resembles that of the intensive type, and it is somewhat difficult to tell them apart; but by approaching a point directly below a lamp from a distance of 5 feet or more, looking steadily at the lamp meanwhile, the lamp will appear to grow brighter if the reflector is of the intensive type or to become less bright if the reflector is of the extensive type.

Various types of reflectors besides the prismatic type are used with tungsten lamps, such as *opal reflectors*, *milk-glass reflectors*, and *art-glass reflectors*. Each type has its place in illumination, and the architect or illuminating engineer selects the type best suited to the purpose at hand.

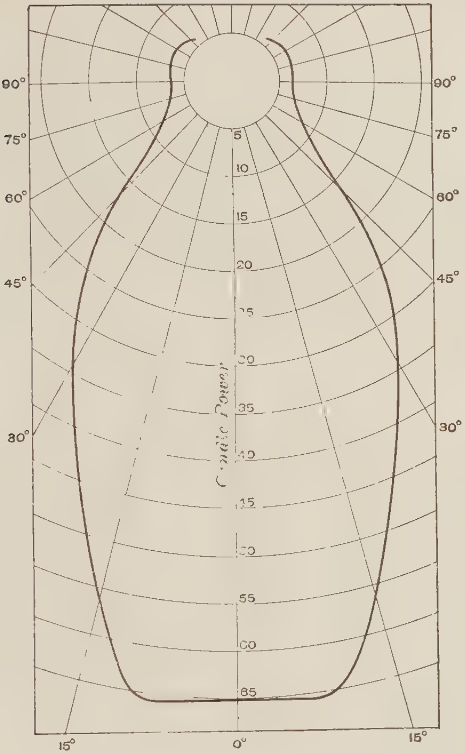

90°
90°
75°
75°
60°
60°
45°
45°
30°
30°
5
10
15
20
25
30
35
40
45
50
55
60
65
Candle Power
15°
0°
15°

FIG. 30

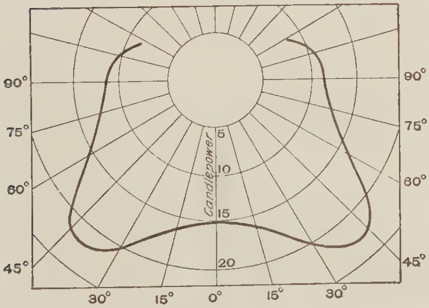

90°
90°
75°
75°
60°
60°
45°
45°
5
10
15
20
Candlepower
30°
15°
0°
15°
30°

FIG. 31

THE NERNST LAMP

71. The **Nernst lamp,** Fig. 32, is an ingenious device, consisting essentially of *glowers*, *heaters*, *ballast*, and *cut-out device*. The glowers produce the light. They are made of combinations of rare earths of volcanic production, which are insulators when cold and conductors when hot. The heaters are made of platinum wire, usually wound over thin porcelain tubes and embedded in a white-cement paste. When the lamp is first connected in circuit, the current in the heaters warms the glowers until they become conductors. Current in the glowers then further heats them until they begin to glow, when the cut-out device, operated by an electromagnet in series with the glowers, opens the circuit of the heaters, leaving the glowers in service alone. Fig. 33 shows a burner with a glower-and-heater unit attached to the bottom of the porcelain disk.

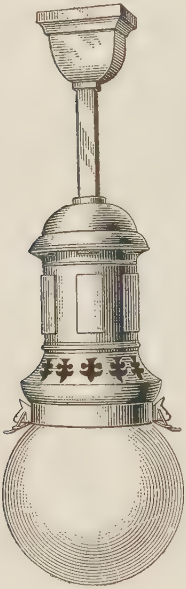


FIG. 32

The ballast is iron wire, the resistance of which increases with rising temperature. The ballast is connected in series with the glowers, so that an increase of current increases the resistance of the ballast and thus counteracts the decreasing resistance of the glowers. Nernst lamps do not operate well on circuits that have poor voltage regulation. When current is first turned on, the lamp gives about one-third full brilliancy, increasing to full brilliancy in about 10 seconds.

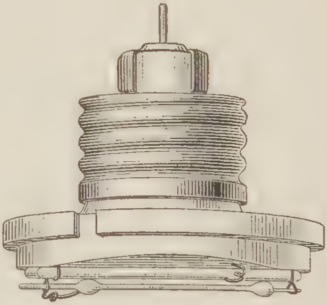


FIG. 33

72. The disadvantages of the Nernst lamp in comparison with its chief competitor, the tungsten lamp, are higher first cost, higher maintenance cost, greater sensitiveness to voltage variations, and sluggishness in starting. Constant attendance is necessary to replace burned-out heaters and glowers, making the cost of maintenance high and the service generally less satisfactory than that of the more modern tungsten lamps.

The manufacture of Nernst lamps has been discontinued, though many thousands were sold before the introduction of the tungsten lamp and many are still in use.

THE NITROGEN-FILLED LAMP

CONSTRUCTION

73. Principle of the Nitrogen-Filled Lamp.—The so-called *nitrogen lamp*, or more properly the **nitrogen-filled lamp**, is a tungsten lamp of high efficiency developed as the result of experiments seeking the operation of tungsten lamps at high efficiencies without blackening of the bulbs. The rapid blackening of the bulbs of poorly made tungsten lamps is due to the chemical action on the filament of water vapor within the bulb; but the chief cause of the gradual blackening of ordinary, well-made tungsten lamps is the evaporation of the filaments. By introducing nitrogen into the bulb of a tungsten lamp, the rate of evaporation of the filament is decreased; also, the lamp can be so arranged that the heat currents in the nitrogen gas change the location of any deposit so that the part of the bulb opposite the filament does not darken.

74. Filaments and Leading-In Wires.—Higher efficiency and longer life are obtained in the nitrogen-filled lamp by the use of a filament of comparatively large diameter, but occupying a small space, because the success of the lamp depends in part on securing the proper gas currents due to convection. The large diameter effective in setting up convection currents must be obtained without a correspondingly low resistance; and this is accomplished by winding the filament in the form of a tightly coiled helix, as in Figs. 34, 35, and 36. The larger the helix diameter, the higher is the efficiency that can be obtained; but the helix diameter is generally limited by the sagging of the heated filament that is likely to occur if the mandrel on which the helix is wound is too large relative to the size of the wire.

Platinum is not used for the leading-in wires of nitrogen-filled lamps; in the larger sizes, which take currents as high as 20 amperes and over, special alloys with the same coefficient of expansion as the glass of the bulb are used. In many of the larger lamps, short leading-in wires pass through the lower end of the bulb, as in Fig. 36; in others, the leads are brought in from the top, as in Figs. 34 and 35. The latter method requires more care in the construction of the seal, because of the rising currents of heated gas.

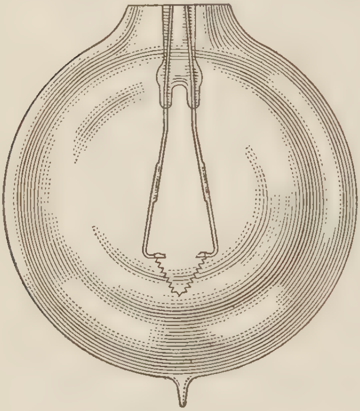


FIG. 34

75. Bulbs.—Owing to the presence of the gas in the nitrogen-filled lamp, more heat is carried to the bulb than in the ordinary incandescent lamp. The gas currents carrying this extra and relatively large amount of heat travel upwards from the filament and strike a comparatively small area of the bulb, which thus tends to become overheated. Such overheating will cause the liberation of enough water vapor to attack the filament chemically and thus cause rapid blackening of the bulb; for this reason, the filament should be placed in the lower part of the bulb, as shown in the illustrations, from all of which the lamp bases are omitted. It is also desirable, though not necessary, to make the bulb of a height greater than its horizontal diameter. By careful design, bulbs of nitrogen-filled lamps can be made smaller than those of ordinary vacuum lamps of the same wattage. The bulbs of such lamps become hotter than those of the ordinary lamps. Several kinds of special heat-resisting glass have been tried for the bulbs of nitrogen-filled lamps in an attempt to make smaller bulbs possible. In addition to the styles of bulbs shown in Figs. 34, 35, and 36, bulbs closely resembling in shape those of ordinary tungsten or carbon lamps are used.

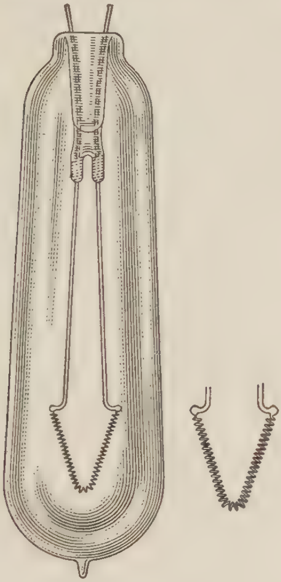


FIG. 35

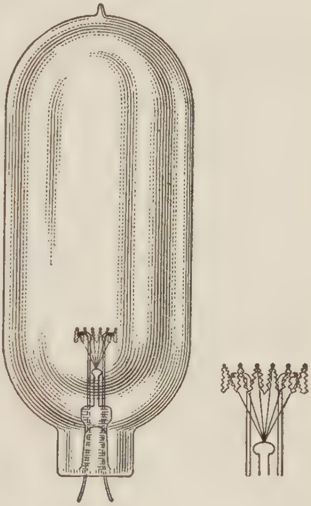


FIG. 36

COMMERCIAL CHARACTERISTICS

76. Types and Applications of Nitrogen-Filled Lamps.—As previously stated, the higher efficiencies in nitrogen-filled lamps are obtained with large filaments taking large currents. This type of lamp is therefore well adapted to large units. These take currents of 20 or more amperes and, except in the largest sizes, are therefore best operated on alternating-current circuits by means of small transformers giving a voltage adapted to the size of lamp required. Efficiencies as low as .4 watt per candle are obtained with the large units.

Small units taking 10 amperes or less and voltages as low as 4 or 5 can also be made, though the efficiencies are somewhat lower than those of the high-candlepower lamps. These small-unit lamps are adapted for series street lighting on 6.6-ampere circuits and for stereopticans and automobile headlights.

High-candlepower lamps to be operated on standard 110-volt lighting circuits can also be made. Large units give several thousand candlepower at efficiencies of about .5 watt per candle. The efficiency of smaller units is ordinarily not so high.

High-candlepower, multiple, nitrogen lamps are particularly adaptable to the lighting of large areas where the units must be hung high, though with suitable globes they can be used where the ceilings are low. They are useful for lighting outdoor areas in athletic parks, amusement parks, etc. and for display lighting and other publicity purposes. The nitrogen lamp is preferable to other incandescent lamps for series street lighting.

77. Advantages of Nitrogen-Filled Lamps.—Besides its high efficiency, the nitrogen-filled lamp has features that may prove of advantage in certain cases. Owing to the high temperature at which the filament is operated, the nitrogen-filled lamp gives a light very closely approximating daylight in color, in which respect it is excelled by only one other type of lamp, the Moore lamp, a type of incandescent tube described in *Electric Lamps*, Part 2. By the use of special color screens, a true daylight color can be obtained at a considerable sacrifice of efficiency. The high intrinsic brilliancy of the filament of a nitrogen-filled lamp also adapts it to projection work, as in stereopticans. The nitrogen-filled lamp also retains constant characteristics throughout its whole life; the ultimate failure of this lamp is due to breakage of the filament.

Owing to the form and arrangement of the filament of the nitrogen lamp, the ratio of its mean spherical candlepower to its mean horizontal candlepower is about 90 per cent., that is, 10 to 12 per cent. higher than the ordinary tungsten lamp. This uniformity of the light distribution, combined with the compactness of the light source, greatly facilitates the design of reflectors to obtain almost any desired distribution of light.

ELECTRIC LAMPS

(PART 2)

ARC LAMPS

INTRODUCTION

THE ELECTRIC ARC

1. If two rods of conducting material attached to the terminals of a dynamo or some other source of electromotive force, as shown in Fig. 1, are touched together, electricity will flow from one to the other through the point of contact. If the conductors are drawn apart gradually, the flow between them will continue, not through the air as does a static discharge, but through a gaseous path composed of the constituents of the conductors vaporized by the heat of the arc. The arc is so called because in Sir Humphry Davy's original experiments the carbon conductors were held horizontally and the arc was bowed up by the convection currents (the heated air rising) into a pronounced arch, or arc.

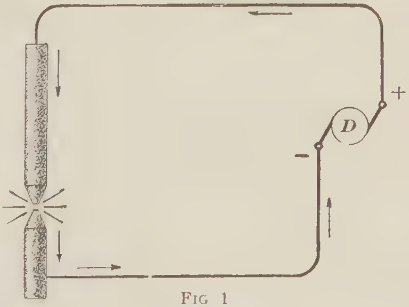


Fig 1

An arc can be drawn between almost any two conductors. Materials of low melting point or those which are readily oxidiz-

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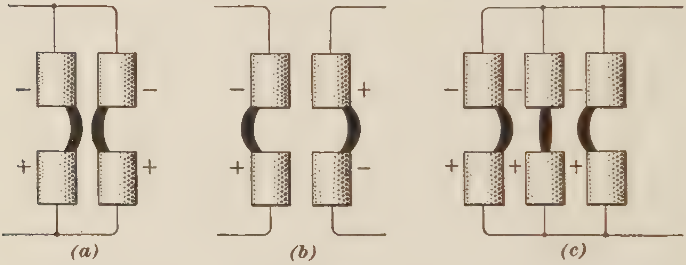
able are, however, rapidly wasted away, and in practice the choice of electrode material for arc lamps is limited. The ideal electrode has yet to be found, and manufacturers are continually searching for a material that will produce brilliant illumination without being rapidly consumed.

2. The electric arc is a conductor and as such is acted on by a magnetic flux; but, unlike most conductors, the arc is flexible and can be distorted by magnetism. A continuous flux causes a direct-current arc to bow to one side; if the flux is strong enough, the arc will be broken, or "blown out." In some lamps the arc is thus made to take a characteristic shape, and magnetic blow-out coils are used to extinguish the arcs caused by opening switches and circuit-breakers. An alternating-current arc in a continuous flux or a direct-current arc in an alternating flux is driven rapidly from side to side, appearing as two separate arcs. Two similar arcs side by side are attracted toward each other as in Fig. 2 (*a*) and (*c*); arcs of dissimilar polarity are repelled, as shown in (*b*).



(*a*) (*b*) (*c*)

FIG. 2

CLASSIFICATIONS

3. As sources of light, electric arcs can be divided into three classes:

1. Arcs in which the light is produced mainly by the incandescence of the electrodes. The carbon arc is most satisfactory for this purpose; because carbon can withstand a much greater temperature than almost any other known substance.

2. Arcs in which the light is produced from the arc flame by evaporating from the electrodes substances that give a luminous spectrum. For such lamps, carbons are impregnated or cored with light-producing chemicals, generally calcium compounds, that evaporate, or volatilize, in the heat of the arc, producing a highly efficient light.

3. Arcs in which the arc stream itself gives a luminous spectrum. Carbon electrodes are excluded from this class, because the carbon arc stream is practically non-luminous. The light-giving material is used as the cathode, or negative electrode; the anode, or positive electrode, can be any conductor, provided it is kept cool enough to be non-consuming. With any type of arc, the gases from the cathode carry the electric current, even though, as in the ordinary carbon arc, the anode gases are in great preponderance owing to the higher temperature of the positive carbon.

METHODS OF RATING

4. The candlepower of any arc lamp varies so much in different directions that the only fair way in which to compare the illuminating effects of arc lamps is to average the light intensities from each lamp in all directions, or possibly in all directions in the lower hemisphere only. The average of the light intensities in all directions is called the *mean spherical candlepower*, and the average for the lower hemisphere the *mean lower hemispherical candlepower.* Since the useful light is almost wholly in the lower hemisphere, the latter unit is most often employed, when candlepower is stated.

Owing to the difficulty of measuring large candlepowers, arc lamps, like incandescent lamps, are customarily rated in watts; also, as with incandescent lamps, the efficiencies of arc lamps are specified in watts per candlepower. Both the watts input and the efficiency take into account the energy required by the operating mechanism or other auxiliaries of the lamp.

OPEN CARBON ARC CHARACTERISTICS

5. General Appearance.—The electric arc is so dazzlingly bright that it cannot be examined directly with the eye. An open carbon arc with the positive electrode on top, when examined through a blue or a smoked glass or through a pinhole in a piece of cardboard, appears as a violet-colored stream of light surrounded by a green flame that is separated from the light stream by a narrow, dark space, or shadow. After an open arc has been maintained for a while with a carbon separation of about $\frac{1}{8}$ inch, it assumes the characteristic shape shown diagrammatically and enlarged in Fig. 3.

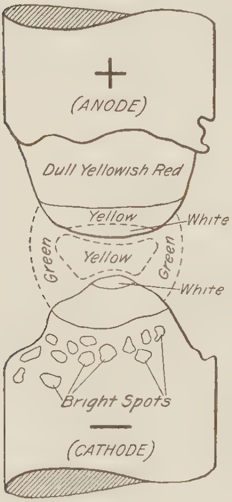


FIG. 3

6. Shape of Carbons.—The ends of both electrodes of an open arc become tapered because of the burning away of the carbon. The lengths of the tapered parts can be made greater by increasing the current or by decreasing the distance between the electrodes. The positive carbon wastes away almost twice as fast as the negative. A white-hot crater forms in the end of the positive carbon, as is indicated by the dotted line in the end of the upper carbon, Fig. 3. The area of this crater can be increased by increasing either the current or the length of the arc. A more or less blunt point, terminating in a white hot spot, is formed on the negative carbon, and, within limits, the larger the current or the shorter the arc, the sharper will be the point.

7. Temperature and Composition.—The temperature of the crater of the positive carbon of a direct-current arc is the highest ever produced artificially. A valuable characteristic of carbon is that it never melts, but vaporizes without melting at approximately 3,720° C. This temperature is more than twice that required to melt platinum (1,755° C.); it is well above the temperature at which tungsten melts (3,000° C.), and is nearly two-thirds the temperature at the surface of the sun (estimated at 6,000° C.).

As previously explained, the conducting vapor from the cathode carries the current; but the intensely heated carbon vapor from the crater in the anode causes the flame. The thin layer of carbon vapor immediately surrounding the crater is condensed into the minute particles of solid carbon that form the purple-colored body of the arc; the combustion of these intensely heated particles where they come into contact with the air forms the flame. If the arc becomes too long with a fixed current or the current too small with a fixed length of arc, the flame runs up around the positive carbon, wasting it rapidly away and heating the lamp mechanism.

8. **Stability.**—The voltage below which an open carbon arc cannot be maintained is between 35 and 40. With constant current, the total voltage drop across the arc increases with the length of the arc; but with a constant arc length, any increase in the current causes such an increase in the cross-sectional area of the arc that the voltage required to maintain the arc becomes less as the current becomes greater. On a constant potential circuit, therefore, an arc of fixed length is in unstable electrical equilibrium, and the current must be limited by external resistance, or *ballast*, in series with the arc. Too much current for a given length of arc causes pronounced hissing, accompanied by a sudden drop of about 10 volts across the arc and by a decreased amount of light. To prevent hissing, arcs of very large capacity, say, 150 to 200 amperes, must be comparatively long and the carbons must be large. For a long arc or a small current, a high external resistance is necessary, and for a short arc or a large current the external resistance can be much lower. Very large arcs, such as are used in electric furnaces, can be maintained without any external resistance other than that in the leads and generating apparatus.

On account of their inherent instability, it is impossible for two or more arcs to operate in parallel, without individual ballasting. The action is the same as two series generators operating in parallel without equalizing connections. One arc tends to take excessive current and the other goes out.

9. Voltage and Current.—The most satisfactory commercial voltage across a $\frac{1}{8}$-inch carbon arc in open air is from 40 to 55. If the carbons are pulled apart far enough to require a much higher voltage than this with normal current, they will flame badly, the light will be poor, the upper carbon will be consumed rapidly, and the lamp mechanism will be heated excessively.

The temperature of the crater of a carbon arc remains constant at the vaporization point of carbon, regardless of the current. An increase in current, however, increases the area of the crater, and, hence, the light emitted. Powerful lamps, such as searchlights using very large currents, require correspondingly large carbons to carry the current and to provide sufficient surface on the anode for the large crater, because any tendency of the crater to exceed the area of the face of the anode and extend up the side of the slope (see Fig. 3) causes hissing. Ordinary lamps for street and commercial illumination take from 3 to 15 amperes. The current actually taken by an arc lamp on a constant-voltage circuit depends solely on the length of the arc and on the amount of ballast.

10. Composition of Electrodes.—Most of the better grades of carbon electrodes are made from a paste of lampblack, or a mixture of lampblack with gas-retort carbon or graphite, and a suitable binder. The paste is formed into rods, sometimes by heavy pressure in molds, but more frequently by squeezing it through dies. The rods are cut into proper lengths, dried slowly, and then baked at high temperature, both to harden them and to burn out impurities.

Pure-carbon electrodes are made in various grades of hardness. Hard carbons with central cores of softer carbon are also available. Soft carbons rich in lampblack give better light for the same amount of power and steadier arcs than harder carbons containing more graphite. More light is given by a direct-current arc with solid carbons than with cored carbons, on account of the lower temperature of the crater with cored carbons. Soft carbons are consumed rapidly; hence, they are not used so much in the United States as in Europe, where the cost of carbons and of trimming is much less.

11. In Fig. 4 is shown a *cored carbon*, so called from the core *a* formed by filling a small hole in the center of the carbon with much softer material than the surrounding part. The soft core vaporizes more easily than the rest of the carbon and produces a supply of vapor that increases the stability of the arc and keeps it more nearly stationary. Cored carbons are particularly useful for alternating-current lamps, in which the arc is liable to be unsteady and flickering. The cored carbon allows a longer arc for a given voltage than would be practicable with solid carbons. Some makers use cored carbons for both the upper and lower electrodes of alternating-current lamps, and others use them for the upper electrode only. Cored carbons are generally used with alternating-current lamps only, as plain carbons usually give satisfactory service with direct current. Searchlights, however, are operated almost wholly by direct current, and the positive carbon is generally cored, as it is important to keep the arc in one place.

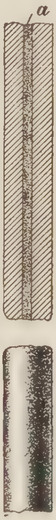


FIG. 4

12. In any case, the carbon should be as pure and as uniform in quality as possible. Impurities may interfere seriously with the quality of the light, because they vaporize at much lower temperature than carbon and thus tend to lower the temperature and the light-giving properties of the arc. Hard spots in the carbon will cause uneven burning, and carbons that are too soft are liable to flame badly. Hard spots will also give rise to hissing. Carbons for open-arc lamps are usually electroplated with a thin coating of copper to increase their durability and conductivity and make them burn more uniformly.

Carbon is one of the very few materials that can be used successfully for electrodes in an alternating-current arc lamp. With most materials, the arc goes out at each current reversal, unless the voltage is very high. The intensely heated vapor of the carbon arc probably does not cool enough during the current reversal to establish a resistance requiring higher than the arc voltage to start current in the reverse direction.

13. Light Characteristics.—The light from a *direct-current, open, carbon arc* depends on the size and make of carbons, the length of arc, and the current. The light varies with the area of the crater, which can be increased by increasing either the current or the length of the arc. Some light is cut off by the lower of two vertical carbons, making short arcs disadvantageous, and pointing to the advisability of small lower carbons.

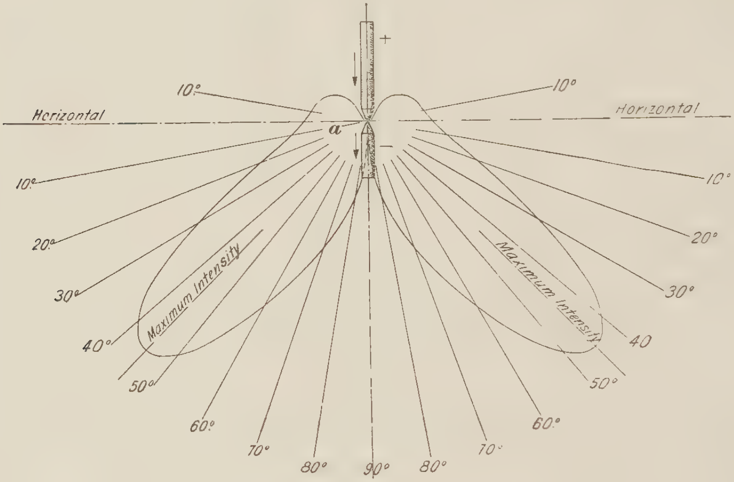


Fig. 5

On the other hand, having both carbons of the same diameter is an advantage in *trimming*, or replacing electrodes, because it is customary to replace the shorter negative carbon with the unburned part of the positive carbon.

At a given angle with the carbons, the light from such an arc is fairly uniform in all horizontal directions around the lamp, but varies considerably at different angles, as shown in Fig. 5, in which the intensity in any direction in a vertical plane is indicated by the distance to the curve from the center *a* of the arc. The intensity is greatest at angles of 45° below the horizontal, because in those directions the crater is screened neither by the carbons nor by the lamp mechanism. This distribution of light is advantageous for street illumination, since the intensity is greatest in the direction in which most light is needed. Such lamps should be connected with the positive carbon above. If there is any uncertainty as to which line is positive, the lamps should be allowed to burn for a short time and the current switched off; the positive carbon can then be identified as explained in Art. **6.**

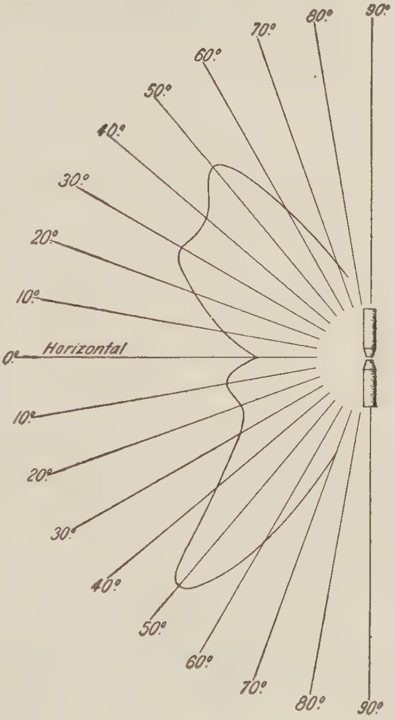


FIG. 6

14. The characteristic light distribution from an *alternating-current open arc* is shown in Fig. 6. In such an arc, the electrodes are alternately positive and negative. No particular crater is formed on either carbon, nor do they become pointed, but remain blunt; also, the arc wanders from point to point. In fact, it is probably this constant wandering that prevents any particular crater from being formed.

The light from an alternating arc fluctuates in synchronism with the current, but with a considerable time lag. This fluctuation is not apparent when viewing stationary objects illuminated by a 60-cycle arc, or even when looking directly at the arc, but is quite perceptible at 25 cycles and is intolerable at 15 cycles. The flicker from a 60-cycle arc is quite noticeable when viewing rapidly moving objects, as they appear to move by jerks. Thus, a cane twirled in the hand appears to rotate by steps, and the field poles of a rotating-field alternator viewed by the light of an arc fed from the alternator appear to stand perfectly still. If the lamp current comes from bus-bars fed by two or more alternators in parallel, the field poles may at times be seen to oscillate slowly back and forth, illustrating the phenomenon known as *hunting*.

In order to obviate the flicker from alternating arcs of low frequency, an Italian concern has developed a three-phase arc lamp. This lamp has three stationary electrodes, connected one to each phase, and one large electrode that is not connected to the circuit, but is lowered until it short-circuits the other three. The current, through magnet coils, then lifts the upper carbon, drawing an arc from each of the lower electrodes. Frequencies as low as 17 cycles per second are said to give very satisfactory results in this lamp. It has not been introduced into the United States.

COMMERCIAL USES OF OPEN CARBON ARCS

15. For street lighting and, in fact, for general lighting of any character, the open carbon arc lamp is practically obsolete. For projection work, however, such as for stereopticons, moving pictures, and searchlights, it is still in common use, the single concentrated source of light produced by the crater being exceptionally advantageous for projection work with either lenses or mirrors.

MOVING-PICTURE MACHINES AND STEREOPTICONS

16. Arrangement of Carbons.—For moving-picture machines requiring large-current arcs, the carbons are usually arranged at an angle of 45° with the vertical, as in Figs. 7 and 8, to secure the maximum amount of light horizontally. In Fig. 8 the screen is shielded from the direct rays of the arc by the reflector r, the projection being obtained, through suitable lenses, by the reflected rays from the mirror M.

17. For stereopticons, in which the current value is comparatively low and space considerations are valuable, the arrangement shown in Fig. 9 is customary. This arrangement has the advantage that the crater is always in the axis of the optical system and is unobstructed by the negative carbon. The characteristic light-distribution curve shown in Fig. 5 does not, of course, hold for this case, in which the crater is not covered by the negative carbon, but the maximum light is given off directly in line with the positive carbon. The feed-mechanism moves the positive carbon forwards and the negative upwards. Such lamps are practically always designed for hand feed, so that any desired adjustment can be obtained. A small colored window in the side of the lamp gives the operator a view of the arc. The right-angle arrangement is not satisfactory above about 25 amperes, on account of the magnetic blow-out action of the current. Below that value it gives a more satisfactory light than any other scheme.

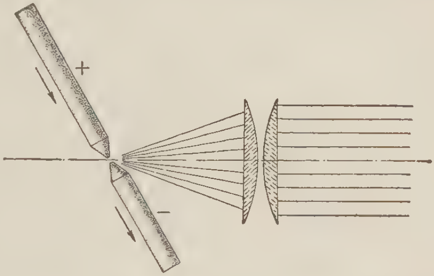


FIG. 7

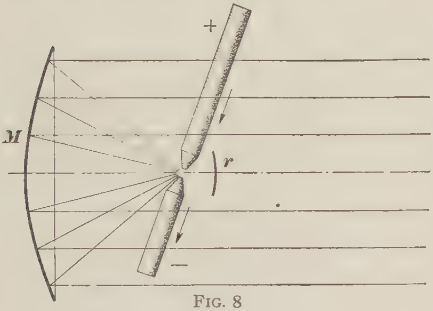


FIG. 8

The arrangement of electrodes shown in Fig. 10 has been tried for alternating arcs with the view of using the light from both carbons. Although this arrangement gives more light as a whole than the usual arrangement, it is open to the objection that there are two light sources slightly separated; consequently, if the picture is not in perfect focus, the image will be doubled as well as blurred and therefore very

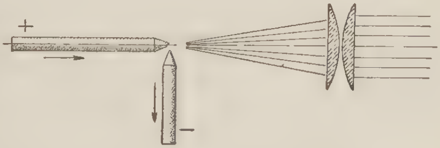


FIG. 9

hard on the eyes. This arrangement, like the 90° arrangement shown in Fig. 9, is impossible with large currents.

18. Current.—The alternating-current arc is very unsatisfactory for projection work. It is inefficient, requiring two to three times as much current as a direct-current arc. The light is usually unsteady on account of the tendency of the arc to wander around over the surface of the electrodes, so that the brightest part of the arc is at times on the side away from the lenses; also, the flickering of the light is objectionable for moving pictures. The current can, of course, be transformed to direct current with a motor-generator, but this transformation is expensive and bothersome. The most satisfactory apparatus at present is the mercury-vapor rectifier in connection with a transformer having sufficient magnetic leakage to supply the necessary ballast effect. Pulsating direct current at the required voltage is thereby delivered to the lamp. The light flickers slightly, but very much less than with alternating current and not enough to be noticeable under ordinary circumstances. The efficiency of such an arc is practically equal to that of the direct-current arc.

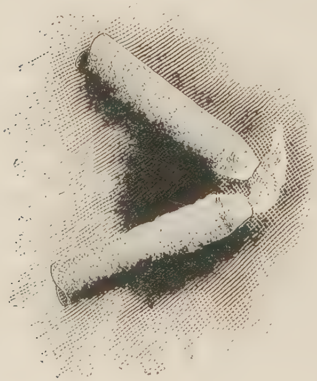
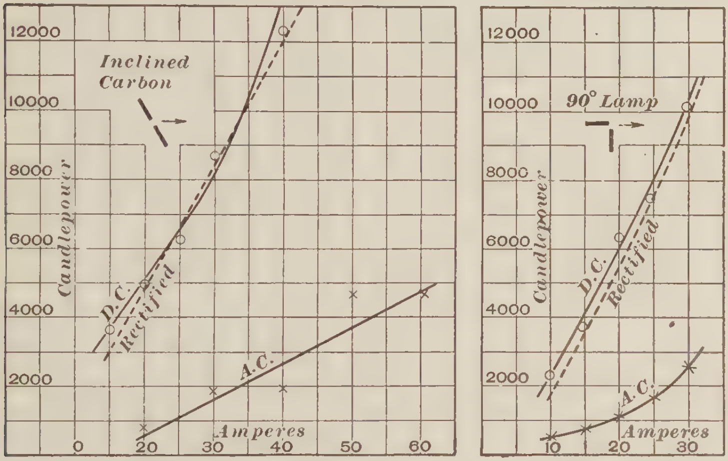


Fig. 10

Satisfactory lighting of the screen with alternating current requires 25 to 30 amperes for stereopticons and 35 to 60 amperes for moving pictures, although it is difficult to maintain a satisfactory arc at this high current value. With direct current, satisfactory results are secured with as low as 10 amperes for stereopticons and 15 to 20 amperes for moving pictures. The relation between current and light is indicated by the curves shown in Fig. 11; these curves are based on experiments, (*a*) showing relations with inclined carbons, and (*b*) with carbons at right angles. It is generally considered that there should be at least 2,500 candlepower for satisfactory stereopticon work with good condensing lenses and a screen of medium size, and 4,000 candlepower for moving pictures.

19. Voltage Regulation.—Inasmuch as commercial direct-current lighting circuits are generally at 110 volts, and sometimes at 220 volts, a rheostat is necessary to bring the arc voltage to its proper value, which is usually not more than 55 to 60. On such a circuit, a large part of the total energy supplied is wasted in the rheostat. When direct current is taken from a mercury-vapor converter, no rheostat is necessary; the voltage reduction is taken care of by the converter outfit.



(a) (b)

FIG. 11

Where alternating current only is available, a choke coil may be used in place of a rheostat, with very great increase in efficiency. The choke coil produces such a low power-factor on the line that many central-station companies have prohibited their use. A small transformer with variable voltage taps on the secondary, and designed with a large magnetic leakage to give satisfactory ballasting effect, may be used without either choke coil or rheostat in series, and gives high efficiency (95 per cent. or more) at a reasonably good power factor. It is not much more expensive than a good choke coil with variable taps.

SEARCHLIGHTS

20. A **searchlight** is essentially a combination of a mirror with an arc so that all the light rays are reflected in nearly parallel directions. Under such conditions, the law of inverse squares, explained in *Electric Lamps*, Part 1, does not hold true. The illumination by searchlight on a distant object is proportional to the candlepower of the arc and to the area of the object circle, or circle of light on the object; the distance makes little difference other than in light absorbed by the atmosphere.

Searchlights find their most exacting requirements in the navy. They are also extensively used on commercial vessels and along the rivers and the Great Lakes, as well as for industrial purposes and for spotlights in theaters.

The standard searchlight of the navy operates at 110 amperes on a 125-volt circuit. It throws a light that is effective at sea for 6 to 8 miles, and when thrown on the clouds, can be seen for more than 30 miles.

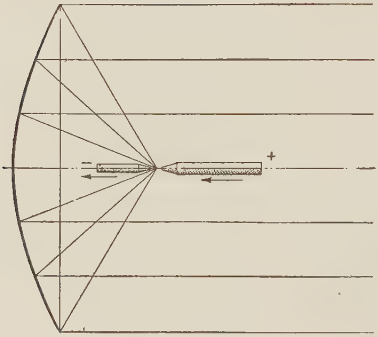


FIG. 12

21. Reflectors and Lenses.—Of the various forms of mirrors that have been used in searchlights, the **parabolic mirror** is the most scientific. The form shown diagrammatically in Fig. 12 is used for all the large searchlights of the United States navy. Some parabolic reflectors are made of polished or silvered metal, others of silvered glass.

The **lens, or Mangin, mirror,** Fig. 13, is of glass with a silvered reflecting outer surface *A* and a refracting inner surface *B*. Both surfaces assist in directing the light rays. As the glass is thicker near the edges than in the middle, the outer rays are refracted, or bent, more than those at the center, and by having the mirror of the proper dimensions, it can be made to give practically the same effect as a parabolic mirror. A

Mangin mirror is cheaper than a parabolic mirror of glass. In the illustration is also shown a shield *r* that screens an object from the direct rays of the arc and in addition assists in the light distribution by reflecting part of the arc rays against the mirror.

22. For some purposes, great penetrating power is the most valuable characteristic of the searchlight; for others, a less intensity but broader range is more valuable. For industrial purposes or for theater spotlights, the latter effect can be secured by throwing the arc out of focus. But for naval work, it is useless to light up the sky, and the same result is secured more efficiently by the use of a group of cylindrical *dispersion lenses* placed side by side in the path of the beam. The light is first converged, or brought together, and then, as the rays cross, they spread out again and continue to spread indefinitely. The light is thus spread out flat, or horizontally, but not vertically, and it is far easier to locate an object near by, as for instance a buoy, than with the concentrated beam. The beam will not of course penetrate so well when thus spread out.

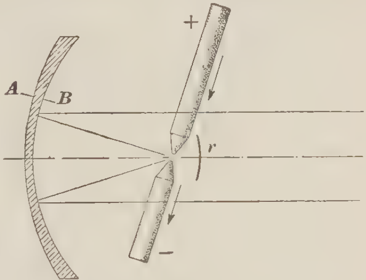


Fig. 13

23. Arrangement of Carbons.—In all direct-current searchlights, the carbons are so placed that the light from the crater of the anode is thrown against the reflector, as in Fig. 12 or 13. To give better light distribution and to equalize the rates of consumption, the anode is usually made the larger of the two carbons. For a 100-ampere lamp, $1\frac{1}{4}$-inch anodes and $\frac{7}{8}$-inch cathodes are recommended.

During recent years a demand for an alternating-current searchlight has been met by the type shown in Fig. 14. Since, in an alternating-current arc, the light is secured from both carbons and also to no little extent from the arc itself, the carbons are arranged at right angles to each other, and at an angle of 45° to the axis of the reflector. In this case, since the light source is of much greater area than in the direct-current lamps, the beam cannot be made so concentrated and hence has not so great penetrating power as has the beam from the direct-current searchlight. This type of lamp is mostly used for industrial purposes around large cities.

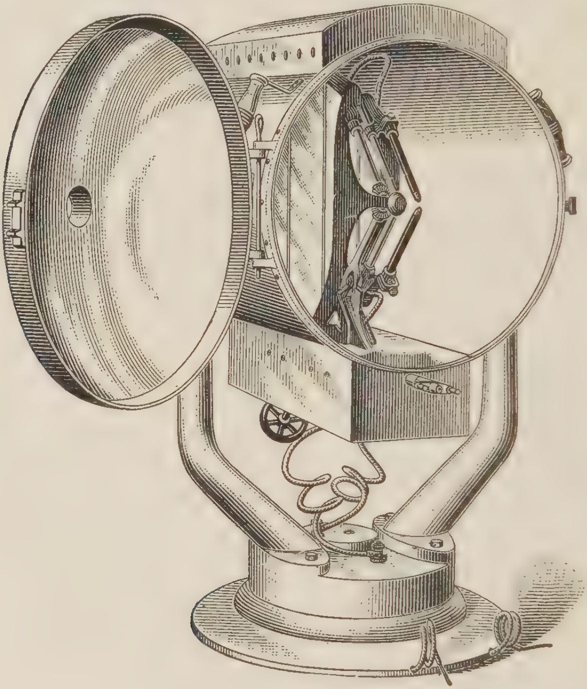


FIG. 14

24. **Feed-Mechanisms.**—Since the chief light source, the crater, must always be kept exactly at the focus of the reflector, a search-lamp mechanism must be arranged to move the carbons toward each other, as they are consumed, at such a rate that the position of the arc is not changed; such a device is known as a *focusing mechanism*. As gravity cannot be depended on in naval work, a positive screw feed is used. The two carbon holders are actuated either by separate screws geared together

or by a right-and-left thread on a single screw (right-hand thread on one end and left-hand thread on the other). The gear ratio or the ratio between the pitches of the two threads is equal to the ratio between the rates of consumption of the carbons.

In one type of mechanism, a small motor rotates the screw and drives the two carbons toward each other, being so connected as to operate only when the voltage across the carbons exceeds the proper value. When the power is thrown on, provided the carbons are separated as they normally should be, no electricity flows except through the shunt motor, which feeds the carbons together until they touch. The voltage across the carbons immediately drops, and the feeding stops. A series magnet then draws the negative carbon back, starting the arc. As the carbons burn away, the voltage between them increases until the feed motor is again started, and the carbons are fed toward one another until the potential difference drops.

In another popular type of mechanism, the feeding is accomplished by a pawl and ratchet actuated by a shunt magnet. When the voltage over the arc, and hence over the shunt coil, exceeds the proper value, the armature attraction exceeds the pull of a retaining spring and drives the ratchet forwards one tooth; then the current through the coil is interrupted by a contact device. The armature is then returned to its neutral position and the operation is repeated, the armature vibrating back and forth until the carbons are fed sufficiently close together to decrease the voltage.

With both types of mechanism just described the arc can be focused, that is, moved forwards or backwards, and the carbons can be adjusted both vertically and horizontally to get them exactly in the focal axis. The automatic mechanism can also be disconnected entirely, and the feeding done by hand, when desired.

25. Searchlight Control.—The direction of small searchlights is controlled entirely by hand, but the larger lights used in the navy are arranged for remote electrical control. Small motors mounted in the base move the searchlight barrel in both horizontal and vertical directions in synchronism with the sight bar on a controller mounted in a convenient location on the deck or the bridge. A shutter in front of the glass door can completely obscure the light, either for signaling or to conceal the location of the ship, and the sight bar enables the searchlight to be accurately sighted even with the shutter closed.

ENCLOSED CARBON ARC CHARACTERISTICS

26. Advantages of Enclosed Carbon Arcs.—The carbons of the open-arc lamp have comparatively short life, not over 15 hours. Some lamps have been made to burn longer by using two pair of carbons in each lamp, the feed mechanism being so arranged that only one pair is in use at a time. The cost of carbons and the cost of changing them are high, however, and the lamps are too dirty for indoor use in most places. For a number of years, therefore, this type of lamp has been almost entirely replaced by the **enclosed-carbon lamp.**

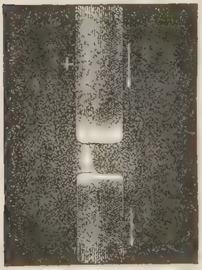


FIG. 15

The enclosed arc differs from the open arc in that it is surmounted by a small inner globe that admits only enough air to prevent deposits of carbon on the globe. In this neutral atmosphere, the carbons waste away very slowly; the same carbons that would burn only 6 or 7 hours in the open air, last from 100 to 150 hours when burning in a proper enclosure.

27. Appearance.—A good general idea of the appearance of the direct-current enclosed arc can be had by referring to Fig. 15, which should be compared with Fig. 3. The principal difference is that in the enclosed arc the carbons do not take on the pointed shape; their ends remain comparatively flat, largely due to the tendency of the arc to shift its position continually. The light given out is softer and more uniform, is more tinged with the violet rays, and has less of the dazzling appearance characteristic of the open arc.

28. Illumination Characteristics.—The distribution of light from an enclosed carbon arc is subject to considerable variation, depending on the shape and the density of the opal enclosing globe, on the position of the arc in the globe, on the composition of the carbons, and on the amount of air admitted to the inner globe. Consequently, it is almost impossible to obtain two exactly similar curves of distribution even with lamps supposed to be duplicates. The curves in Fig. 16 are typical for enclosed-arc lamps with clear outer and opal inner globes and with the arcs in the position taken when approximately one-half the carbons has been consumed. Curve *A* represents the distribution of a 6.6-ampere direct-current series arc; *B*, that of a 5.5-ampere direct-current multiple arc; *C*, that of a 6.6-ampere alternating-current series arc; *D*, that of a 6-ampere alternating-current multiple arc.

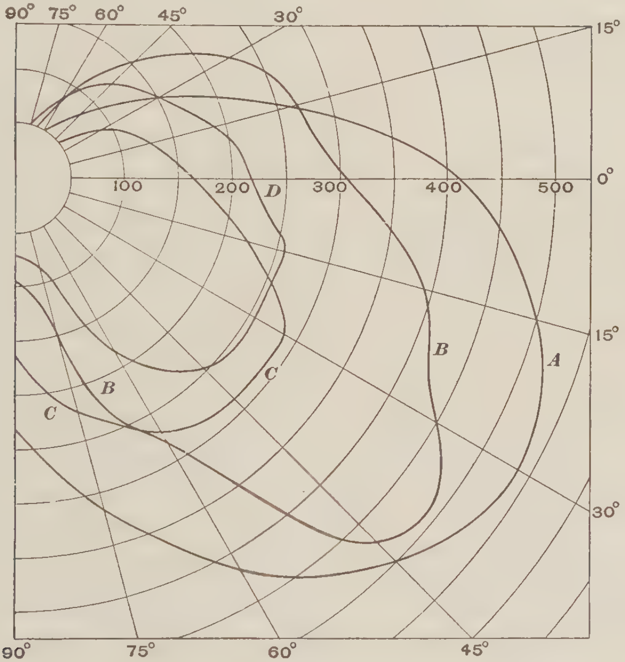


FIG. 16

29. Arc Length and Voltage.—For most satisfactory operation, the enclosed-arc lamp operates with a longer arc than the open-arc lamp, and still burns steadily without flaming. If a short arc is enclosed, it is found that soot, or carbon, is deposited to such an extent that the light is greatly reduced; long arcs are therefore essential to this type of lamp. The longer arc requires higher voltage, the best results being obtained with an arc length of about $\frac{3}{8}$ inch and from 70 to 75 volts. Blackening of the inner globe may be caused either by wrong length of arc or by insufficient ventilation; too much air, however, causes the carbon to burn away rapidly. If the arc is too short (voltage low), carbon vapor is deposited on the inner globe, blackening it; if too long (voltage high), flaming results, accompanied by great heat that blackens and may even melt the globe. Flaming is also caused by too much air and is quite likely to occur when the lamp is first started after a trim. It may be lessened in alternating-current lamps by digging out the core of the new carbon for about $\frac{1}{8}$ inch.

30. Carbon Life.—The life of the carbons in enclosed-arc lamps depends on their composition, the arc length, and the arc-chamber ventilation. Extremely long life can be obtained only by the use of very hard carbons, a low-voltage arc, and with the barest possible amount of ventilation. These conditions are secured at the expense of good light, and, in alternating-current lamps of low power factor, a careful balancing of advantages and disadvantages is necessary. With a 6.6.-ampere, series, alternating-current lamp, the most satisfactory rate of consumption is about $\frac{1}{10}$ inch of carbon per hour, giving, with 12-inch upper and 7-inch lower carbons, a life per trim of about 100 to 110 hours.

TYPES OF ENCLOSED CARBON ARC LAMPS

CLASSIFICATION

31. There are three broad classes of enclosed-arc lamps, adapted to different circuit conditions. The first class includes *multiple lamps*, which operate on 110- and 220-volt direct-current and 110-volt alternating-current constant-potential circuits. Lamps of the second class, namely, *constant-current series lamps*, are made for both alternating- and direct-current circuits, and lamps of the third class, a combination of the first and the second, operate in multiple-series on constant-potential circuits.

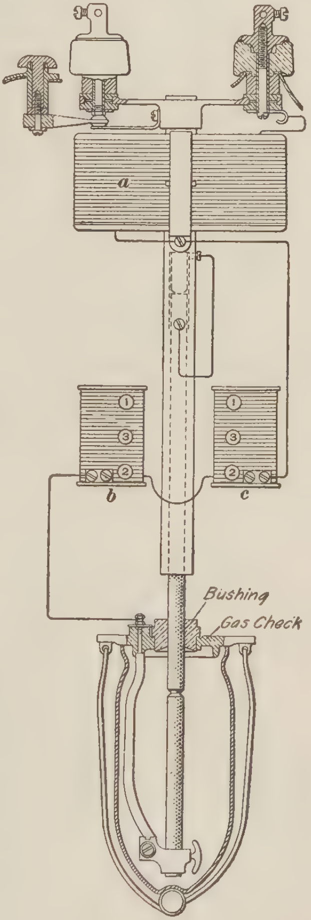


FIG. 17

DIRECT-CURRENT MULTIPLE LAMP

32. Description.—The enclosed-arc lamp for direct-current, constant-potential circuits consists essentially of a pair of solid carbons, a resistance, and magnets for striking the arc. The upper carbon is generally 12 inches long, and the lower carbon $4\frac{1}{2}$ inches. On the 110-volt multiple lamp, the resistance is usually sufficient to adjust the lamp for circuits of 100 to 125 volts. The arrangement of parts is shown in Fig. 17. The arc is in series with the steadying resistance *a* and the magnet coils *b* and *c*. These coils draw up the armature, which is fastened to a clutch (not shown). When the lamp is out of service, the carbons are together; in starting, the current in the magnets, limited only by the resistance *a* and the resistance of the carbons, causes the armature to be raised and with it the upper, or positive, carbon, drawing the arc. The current decreases as the arc lengthens, until a position of stability is reached where the magnetic pull can lift the armature no farther. As the carbons burn away the arc lengthens, and the decreased current allows the armature to drop until the clutch strikes the stop, allowing the carbon to feed downwards until it strikes the lower carbon, when it is again drawn up by the magnet.

The clutch is some form of ring or clamp that fits fairly close around the carbon, which it seizes on movement beyond a fixed limit. If made wholly of metal, the clutch is sometimes insulated from the carbon to prevent heating in case the current reaches the carbon through the clutch, owing to the upper carbon not being firmly seated in its holder.

The magnet coils are frequently provided with taps to adjust for different current strengths, the lamp shown in Fig. 17 having three such taps marked *1*, *2*, *3*, giving 4.5, 5, and 5.5 amperes on the 110-volt lamp and 3, 3.25, and 3.5 amperes on the 220-volt lamp. Care must be exercised to connect with taps of the same number in each coil. In another type of lamp, the current is adjusted by placing weights on the armature.

33. Voltage Adjustments.—The voltage over the arc is adjusted by the resistance at the top of the lamp. The direct-current lamp gives the best results when adjusted for about 80 volts at the arc. If this voltage is more than 85, the arc is liable to be very unsteady and more of the resistance should be cut in; if lower than 75, the light is poor, the carbon tips often glaze over with a sort of slag formation that seriously interferes with the proper maintenance of the arc, and some of the resistance should be cut out. With the 220-volt direct-current lamp, the arc voltage ranges from 140 to 165 at 3 amperes, according to the voltage of the supply. Both the 110-and the 220-volt lamps increase the voltage at the arcs slightly when burning with chipped or broken inner globes; the glassware should therefore be inspected when long or unsteady arcs are observed.

DIRECT-CURRENT SERIES LAMPS

34. Differential Lamps.—The constant-current lamp for direct-current series circuits and the multiple-series lamp for direct-current street-railway and power circuits are practically the same, except that the multiple-series lamp has an arc-compensating resistance that is cut in automatically if the lamp fails to start. This compensating resistance takes the place of the resistance of the lamp and keeps the current at the proper value for the operation of the remaining lamps in the series across the 500- or 220-volt mains.

In Fig. 18 are shown the main features of a multiple-series lamp with a *differential mechanism.* A series coil *a* separates the carbons and strikes the arc by lifting one end of a pivoted feed-lever; a shunt coil *b*, working on the opposite end of the feed-lever and electrically connected in shunt with the arc, acts against the pull of the series coil and trips the clutch when the arc becomes too long, thus causing the carbons to feed together as they burn away. The dashpot *c* damps the movement of the feed lever and prevents fluctuations of the arc. The weight *d* on a threaded stud attached to the feed-lever permits accurate arc adjustment. When the carbons of a multiple-series lamp are burned out, a switch *e* is closed automatically, substituting resistance for the lamp; on the series lamp, an automatic short-circuiting switch (not shown in Fig. 18) is provided.

In other types of series or multiple-series lamps, the shunt and series coils are coaxial, one above the other, pulling in opposite directions on the same armature.

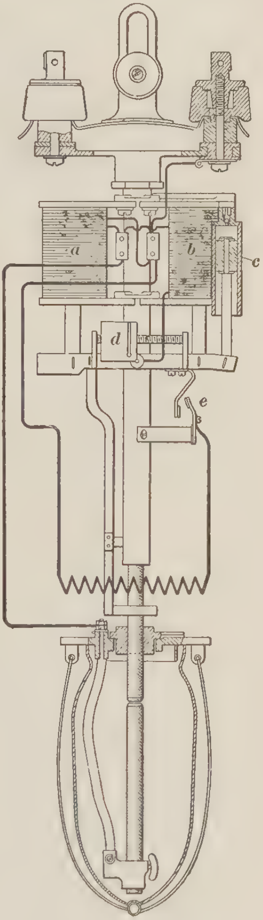


FIG. 18

35. Shunt Lamps.—Series and multiple-series direct-current arc lamps can be operated without a series coil, the shunt coil feeding the carbon in the same manner as in the differential mechanism, but acting against gravity or a spring instead of against the pull of a series coil. When this type of lamp is out of service, the carbons are separated; when the current is turned on, they are drawn together by the action of the shunt coil. Trouble is sometimes caused by the carbons slipping through the clutch, in which case the lamp will not pick up, or start. *Shunt lamps*, as this type is called, do not regulate so well as differential lamps, and are not so much used.

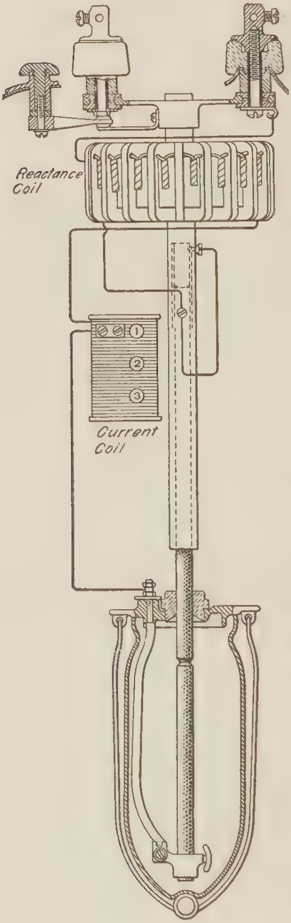


FIG. 19

ALTERNATING-CURRENT MULTIPLE LAMPS

36. 110-Volt Lamp.—The alternating-current multiple lamp is very similar to the direct-current multiple lamp; the chief difference in construction lies in the use of a reactance coil instead of a resistance and laminated magnet cores instead of solid cores. The general arrangement of a 110-volt lamp is shown in Fig. 19. The reactance coil can be adjusted for voltages of 100 to 125 and for frequencies of 60 to 133 cycles per second, although the lamp is likely to become noisy on the higher frequencies. In special cases, these lamps are operated at 50 cycles per second; but at lower frequencies the alternations become visible to the eye, causing a flicker too pronounced for general commercial lighting. The arc voltage should be about 72. If it is much higher, the lamp chatters; if much lower, the carbons glaze and the light is poor. The current coil in the lamp shown in Fig. 19 has three taps, allowing for adjustment for 5.5, 6, and 6.5 amperes, values commonly used, although lamps are on the market with a range of 4 to 7.5 amperes. One cored and one solid carbon are generally used, although both carbons may be cored with good results. The power factor of an alternating-current arc without lamp mechanism is about 90 per cent., the arc itself exerting a choking effect of approximately 10 per cent. The power factor of the complete lamp varies with the lamp adjustments, but averages about 80 per cent.

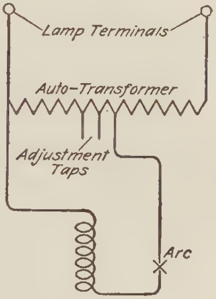


FIG. 20

37. 220- and 440-Volt Lamps. Alternating-current multiple lamps for use on 220- and 440-volt circuits differ from the 110-volt lamps only in the use of a small autotransformer in place of the reactance coil, as indicated in Fig. 20. The voltage adjustment is made by means of taps leading from the transformer.

ALTERNATING-CURRENT SERIES LAMPS

38. Description.—The connections of an alternating-current series lamp, Fig. 21, are very similar to those of a direct-current series or multiple-series lamp. The action of the magnets is differential. A starting resistance limits the current in the series coil to the value necessary to start the lamp. The starting resistance can carry the full working current, so that, if the carbons burn out, the other lamps in the circuit can operate without interference. The automatic cut-out shown in the illustration has a phosphor-bronze spring faced with coin silver contacts $\frac{3}{8}$ inch square. This cut-out short-circuits the arc when it becomes too long, leaving the circuit of the other lamps closed through the starting resistance.

39. Operation.—The arc voltage should be adjusted to about 72. For accurate results, the adjustments should be made after the lamps have been in operation at least 2 hours and are thoroughly heated. Such readings should also be taken with carbons that have been burned and are of an average length. Through a 12-hour run, the variation in arc voltage should not be over 5 volts, and the variation from the pick up to the point of feed should not be over 15 volts. By having a lamp that will regulate within these limits, much steadier and much more satisfactory light will be given.

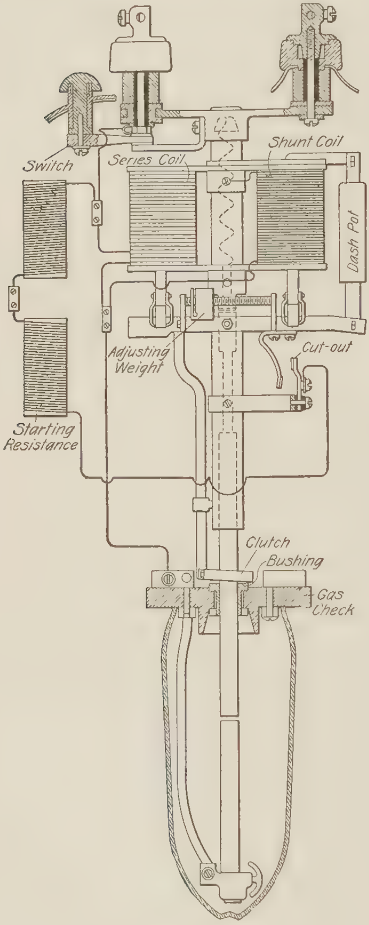


FIG. 21

The quality of light is an important consideration in selecting alternating-current arc lamps. Lamps that regulate closely are better in this respect than those with poor regulation, although the latter may show longer life of carbons. Selection should not therefore be made solely for economy in cost of trimming.

NON-MAGNET MECHANISM

40. In one type of enclosed-arc lamp, the feed mechanism works on the hot-wire principle; no magnets are used. The clutch mechanism is controlled by an expansion wire in series with the arc. When the lamp is first turned on, the carbons remain in contact for a very brief interval until the current heats the expansion wire enough to allow the carbons to be drawn apart by a spring. As the arc lengthens, the current decreases, and the wire contracts until the clutch trips and the carbons feed. The mechanism operates equally well on either direct or alternating current.

CARE AND OPERATION OF ENCLOSED CARBON ARC LAMPS

41. Inner Globes.—In order to obtain long carbon life in an enclosed-arc lamp, the inner globe must be kept air-tight, except for the necessary ventilation. Inner globes with open bases resting on asbestos washers in the lower carbon holder give so much trouble from poor fitting and consequent leakage that they are no longer extensively used. The washers on which such globes rest should not be replaced oftener than necessary, because an old washer usually gives a closer fit than a new one.

The greatest care should be exercised to see that the inner globe rests uniformly and evenly against the finished surface of the gas check (see Figs. 17 and 21) with a moderate pressure. If this pressure is too great, it will result in the cracking or chipping of the inner globe, generally at the point of contact, thus not only destroying the globe, but shortening the life of the carbons. No economy is effected by using chipped or cracked inner globes, owing to the greatly decreased carbon life and the attendant disadvantage and expense of having to trim some lamps on a circuit before the carbons in the others are burned out. In some localities, outage charges for such lamps are also deducted from the earnings of the central station. Outer globes should also be maintained on street systems, as their purpose is to protect the intensely heated surface of the inner globes against rain and snow.

42. The inner globe should be cleaned at each trimming. In large installations, the trimmers are provided with wagons and a supply of clean inner globes. If the lamps have detachable holders, extra holders fitted with new lower carbons and clean globes are carried and substituted for the dirty globes and their holders, which are taken back to the station, where the globes are washed with a small power-driven brush. The trimmer on his route has then simply to furnish a new upper carbon, saving the remnant to be later cut to size for a lower carbon. If the lower holders are not detachable, the lower carbon must be renewed at the installation.

When globes are cleaned on the street, two cloths should be used, one wet and the other dry. The dirty brown deposit that sticks to the inside of the globe can be removed with a weak solution of muriatic acid. Gas caps must be kept clean, the ventilating ducts blown out, and a tight fit maintained between the globe and the cap.

43. Gas Checks.—If a gas check is worn or warped, it should be replaced; a good fit with such a check is impossible, even if the inner globe has a perfect surface, and the resulting excessive ventilation reduces the carbon life.

Aside from the seat for the inner globe, the most important feature of a gas check is the center, or bushing (see Figs. 17 and 21), through which the carbon passes. This center must provide a smooth, accurately fitted opening through which the carbons can pass freely, and, in many cases, must also act as a relief valve for the explosions of gases in the inner globe. Explosions inside the globe are sometimes quite severe and take place generally when a lamp is turned on after being out from 7 to 10 minutes. An explosive mixture of gases forms after the arc ceases to burn, and this mixture is ignited by the arc when the lamp is again switched on. The bushing affords relief by a slight vertical movement that opens ports for equalizing the pressure with the atmosphere, thus tending to neutralize the effect of the explosion and prevent breakage of inner globes. The clearance between the carbon and the bushing should not be greater than a few thousandths of an inch; otherwise, the life of the carbons will be materially shortened.

44. Carbons.—As previously mentioned, excessive ventilation due to defects in globes or gas checks causes short carbon life. Excessive ventilation also occurs if the carbons are too small and, sometimes, if too strong a draft strikes the lamp. Other causes of short carbon life are high arc voltage (long arc), producing flaming; moist carbons; excessive moisture in the air; a loose dashpot, causing the lamp to *jump*, the common expression for continual and more or less violent operation of the feed-mechanism. Excessive fluctuations of current or voltage, causing too frequent starting or stopping, also shorten the carbon life, though this cause is not due to any fault of the lamp.

Moisture on the inner surface of the globes or in the carbons causes the arc to be unsteady at the start and reduces the light to a large extent, by shortening the length of the arc to about one-sixth of its normal length, until the moisture has been dissipated. Hence, carbons should always be stored in a dry place and should be protected on the trimmer's wagon from moisture; they should also be kept free from dust, especially the dust from burned carbons. Oil should not be used on any part of the lamp mechanism, nor should grease or oil be allowed on the carbons, as greasy or oily carbons blacken the globe and cause the lamp to jump badly.

In trimming, the upper carbon should be pushed up into the holder as far as it will go, to insure a good contact. The lower carbon must be cut to exact length, usually 5½ inches, and fastened securely in the lower holder. To insure correct size of carbons, a gauge should be used with two holes marked, for the usual half-inch carbon, .505 and .520. Carbons that easily pass through the smaller hole or that will not pass through the larger one should be rejected. After trimming, the clutch should be tested by pushing up on the rod leading to the armature, which should separate the carbons at least 1 inch in multiple lamps and ½ inch in series lamps.

45. Operating Faults.—A lamp may fail to operate properly for the following reasons:

1. Open circuit, short circuit, ground, or loose connection in the lamp mechanism, causing the lamp to jump or to refuse to light.

2. Carbon or dashpot stuck, preventing feeding. If the dashpot merely works hard, the lamp will start all right, but the voltage over the arc will vary widely, and the arc is liable to break before the lamp feeds. If the dashpot is too loose, the lamp is liable to jump violently after each feed, but to operate quietly otherwise. A tight dashpot is liable to burn out the shunt coil of a differential series lamp. The dashpot plungers should be fitted with the greatest care, especially on series

lamps, so that all dashpots will operate uniformly; also, the operation must not be affected by wide variations in temperature. To meet these requirements, practically all dashpots are now being made of graphite and brass; graphite has a practically negligible temperature coefficient, and works excellently as a plunger in a brass cylinder.

3. Clutch does not catch, preventing an arc from being drawn.

4. Carbons out of alinement, causing them to burn with diagonal ends, which are liable to wedge when feeding. Heavy shadows are cast by the carbons.

5. High arc voltage or air in the globe, causing flaming. A freshly trimmed lamp always flames somewhat, due to the presence of air in the globe.

A lamp that is not giving satisfaction should be replaced and sent to a shop where it can be carefully examined and repaired; if kept in service, it is liable to be entirely burned out and to cause the performance of all other lamps on the circuit to be unsatisfactory. In general, careful attention to the length and size of carbons, accurately fitting glassware, and the habit of keeping the lamps free from dirt will be well repaid by more efficient operation and reduced outages, the term commonly applied to deductions from lighting bills for periods during which lamps do not burn according to the terms of the lighting contract.

INTENSIFIED-ARC LAMPS

DESCRIPTION

46. General Features.—In the United States it has been the custom in selecting enclosed carbon arc lamps to sacrifice efficiency to long life of carbons. In Europe, the contrary has been the case, and carbons of very much smaller diameter are the rule, giving shorter life but greatly increased candlepower. A lamp operating at 6 amperes with 7-millimeter (.28-inch) carbons gives, with a single clear globe, 1,100 mean lower hemispherical candlepower while with 13-millimeter (.52-inch) carbons and the same current the light is only 620 candlepower. Enclosed-arc lamps with small diameter carbons give what is commonly known as an **intensified arc.** A number of such lamps have been developed in the United States to meet the competition of the tungsten lamp for indoor use. Except for purely superficial differences, such as the shape of the outer case, the globe, etc., most of them differ from the ordinary enclosed carbon arc lamp only in being smaller and in using higher current density and carbons of smaller diameter.

When adjusted for 5 amperes and 80 volts at the arc, and equipped with two $12'' \times \frac{1}{4}''$ upper carbons and one $3\frac{1}{2}'' \times \frac{3}{8}''$ lower carbon, this lamp burns about 75 hours. Only the best cored carbons should be used as electrodes.

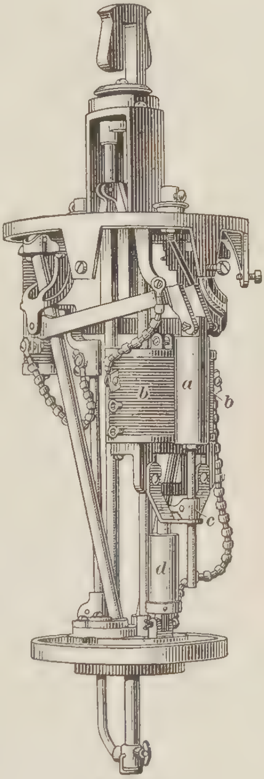


Fig. 22

47. Mechanism.—The mechanism of one of the more distinctive types of direct-current intensified-arc lamps for indoor use is shown in Fig. 22. This lamp differs radically from the previous designs in the arrangement of carbons and in mechanical construction. Two upper (positive) carbons of small diameter are brought obliquely into contact, thereby feeding without a regulating mechanism. The lower (negative) carbon is somewhat larger in diameter and is regulated by means of a series-magnet mechanism similar in action to that described in Art. **32.** The counterweight *a*, Fig. 22, through a system of levers, normally holds the negative carbon up against the positives. When current is turned on, the series magnets *b* draw up a **U**-shaped armature, raising the counterweight and striking the arc. As the arc lengthens, the pull of the magnets lessens, and the weight descends until the clutch *c* slips, permitting the negative carbon again to make contact with the positives, when the magnets again come into action. A dashpot *d* damps the movements of the mechanism. In operation, the upper carbons burn one at a time, alternately, feeding by gravity as they are gradually consumed. No mechanism for a series lamp of this type has been designed, as there is practically no call for such a lamp for outdoor use.

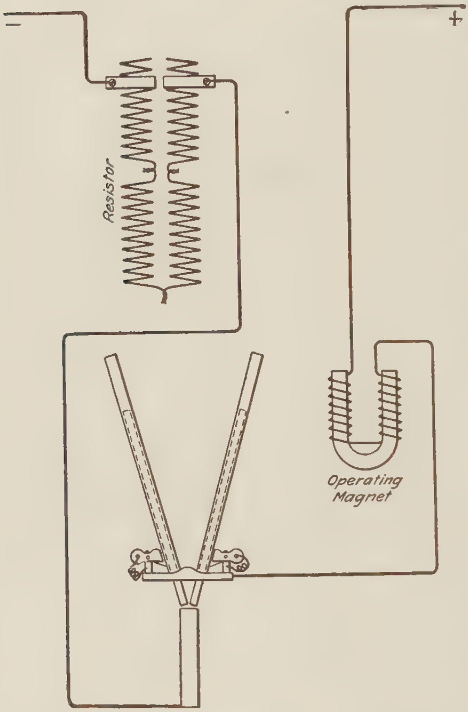


Fig. 23

The general scheme of connections of the direct-current lamp is shown in Fig. 23; the alternating-current lamp differs only in having a reactor in place of the resistor.

LIGHT DISTRIBUTION

48. The gain in lighting efficiency with the intensified arc is due partly to the arrangement of the arc itself and partly to the more efficient distribution. The light that is usually distributed in the upper hemisphere by the ordinary enclosed arc is efficiently diverted into the lower hemisphere by a suitable reflector. This reflector is so designed as to expose but little diffusing surface to the ceiling, thereby raising the lower hemispherical efficiency. The current density in the small carbons is relatively high, and as the heat cannot pass off by conduction, as in the case of large carbons, the end of the electrode becomes incandescent, thereby adding light to that already given by the crater and increasing the efficiency. The characteristic light distribution with an opal art glass outer globe is shown in Fig. 24.

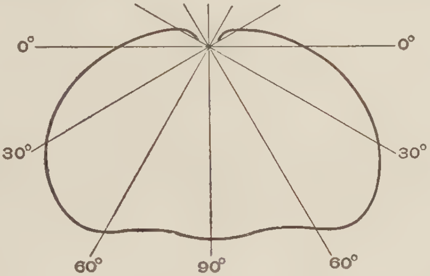


FIG. 24

COLOR-MATCHING OUTFIT

49. The intensified lamp normally gives a light that is whiter than that of an ordinary enclosed-arc lamp, more nearly resembling daylight. For exact color matching, however, the intensified light must be slightly modified by colored screens. A combination of glass pieces of different colors, placed side by side, with a layer of diffusing glass above and below, as shown in Fig. 25, is made in circular form and set into a hinged ring, which is attached to the bottom of a conical hood fastened to the lamp casing, thus forming an efficient color screen. The inside of the hood is provided with a reflecting surface, which surrounds the inner lamp globe and reflects the light downwards

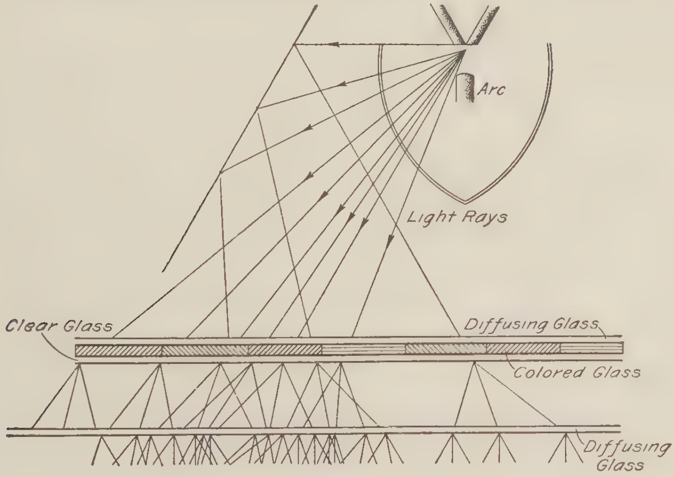


FIG. 25

through the screen upon the samples to be matched, keeping it at the same time from the observer's eyes. The colored-glass pieces remove the excess red, orange, and violet rays, and the diffusing glasses serve to mix the light rays before they pass outside. The color of the resulting light very closely resembles that of the ideal light from the clear north sky. Part of the light is, of course, absorbed by the screens, but the overall efficiency is still high because of the high initial efficiency of the intensified arc

OPEN-FLAME CARBON ARC LAMPS

ARC CHARACTERISTICS

50. Open-flame carbon arc lamps give intense light and are very efficient, requiring only about .2 watt per candlepower. They are much used for spectacular advertising purposes and for lighting large areas, such as public squares, boulevards, and parks. They are particularly suitable for lighting foundries, as the yellow light penetrates smoke and steam more readily than light of any other color.

51. General Description.—As stated previously, when an arc is drawn out beyond a certain length it begins to flame. In the ordinary carbon arc, flaming is a great disadvantage; it becomes an advantage, however, when the carbons are impregnated with a substance that causes the flame to be brilliantly illuminated. The salts (chemical compounds) of calcium and magnesium produce such an effect, the former giving the familiar golden-yellow color, and the latter a white, but less efficient, color. These salts also increase the conductivity of the arc, tending to increase its length, so that flame arcs an inch or more in length are quite common. The greater part of the impregnating material is fed from the anode, because it is hotter than the cathode, which can be plain carbon without detracting from the efficiency of the arc. This arrangement is, however, unusual, both carbons being usually impregnated. The burning of the impregnated carbons is accompanied by the production of noxious fumes, a considerable quantity of ash, and particles of slag, or scoria.

52. In most flame carbon lamps, the carbons are arranged side by side and slightly inclined, so that the lower ends approach each other at an acute angle, as in Fig. 26. The light is free to radiate in a downward direction, and all scoria drops away from the carbons as soon as it forms. Immediately above the arc is arranged a bowl-shaped *economizer*; this serves to protect the arc from air-currents and to shield all except the tips of the carbons from the heat of the arc. Moreover, the economizer soon becomes completely covered with a white ash from the arc and forms an excellent reflector for the light. The arc is made to bow downwards by a small magnet coil (not shown in Fig. 26) immediately above the economizer.

In this arrangement the ends of both carbons are exposed and give off considerable light; about one-fourth the total illumination comes from this source, and three-fourths from the arc proper. In direct-current lamps, the positive carbon is slightly larger in diameter than the negative, so that both burn away at nearly the same rate. In alternating-current lamps, both carbons are equally consumed; hence, the carbons are of the same size.

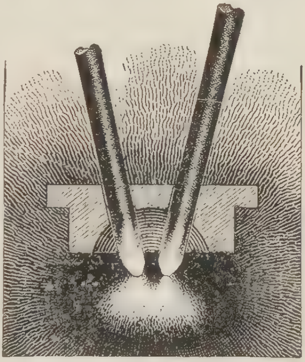


FIG. 26

53. Voltage and Current.—The arc voltage of most of the inclined carbon open-flame lamps varies between 42 and 48. Lower voltage gives poor light and causes the arc to flicker, and with higher voltage the carbons are consumed too rapidly and the lamp burns unsteadily. The low arc voltage would make the lamps inefficient if connected in multiple on 110-volt circuits, because more than half the voltage would be lost in regulating resistance; with 110-volt energy, such lamps are therefore usually burned two in series.

The current is about 10 amperes in nearly all open-flame carbon arc lamps. The carbons are of small diameter, giving intensified arc characteristics that add greatly to the efficiency of this type of lamp.

54. **Electrodes.**—The rate of electrode consumption in an open-flame carbon arc must be fairly rapid to feed sufficient impregnating salts into the flame; the carbons are usually arranged in **V** form, and must necessarily be of small diameter to secure even consumption and steady light. The electrodes must therefore be quite long—16 inches in the 10-hour lamp and 24 inches in the 17-hour lamp—and, even then, daily trimming is necessary. Maintenance is expensive, for the electrodes cost about 15 cents a pair.

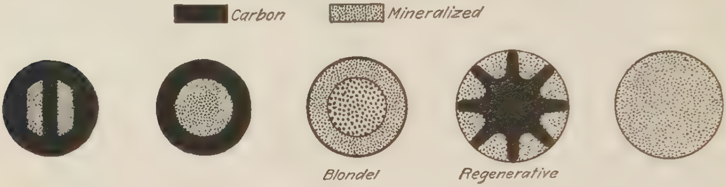


Fig. 27

Flame carbons consist of two sections; one very soft, composed of a mixture of fine carbon and the impregnating mineral salts, and the other a hard, firmly compressed carbon to give mechanical strength. Various arrangements of these two parts are in use, as shown in Fig. 27, and a metallic core, as shown in Fig. 28, is nearly always inserted to give added conductivity. The metallic core is usually at one side of the carbon, instead of in the middle, and in trimming, the wire must be placed so that it will be on the side away from the arc; otherwise, considerable flickering will result.

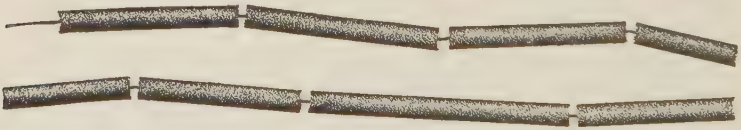


Fig. 28

LIGHT DISTRIBUTION

55. The curves *a* and *b*, Fig. 29, represent the light distribution from a direct-current flaming arc and from a direct-current enclosed-carbon arc, respectively, as determined by tests. The two curves have the same general shape, showing that the light is distributed from both lamps in very much the same way; but the flaming arc gives off nearly six times as much light as the enclosed arc. The maximum light from the flaming arc is in the angular space between 30° and 75° below the horizontal, and is slightly decreased directly under the lamp. During the tests the flaming-arc lamp had an opalescent globe, and the enclosed-arc lamp had an opalescent inner globe, but no outer globe.

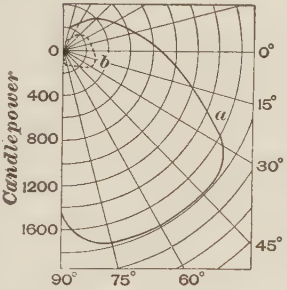


FIG. 29

56. In order to secure distribution of light more suitable for street lighting than that shown in Fig. 29, a number of the manufacturers are equipping their lamps with inner reflectors or shades intended to modify the natural light-distribution so

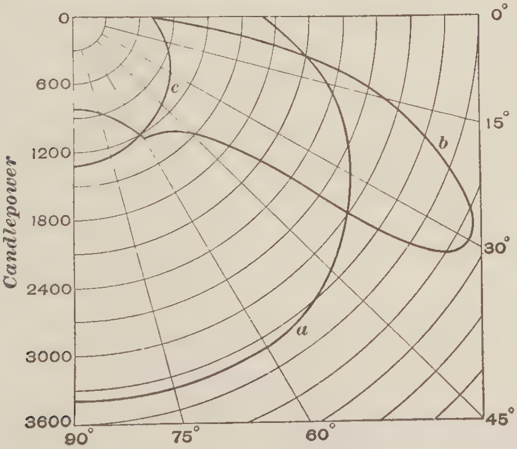


FIG. 30

as to give off less light directly under the lamp, and more at the more useful angles (15° to 40° below the horizontal). In this way, the street or the parkway is not so brightly lighted immediately under the lamp, but is better lighted at points intermediate between lamps. Distribution curves for a direct-current flame arc lamp with inclined electrodes are shown in Fig. 30. Curve *a* shows results with a clear outer globe; curve *b*, those with a prismatic arc-shade and a clear outer globe; and curve *c*, those with an opal outer globe.

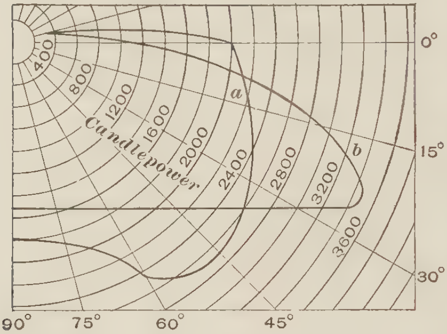


FIG. 31

In Fig. 31 is shown the distribution curves for an alternating-current flame arc lamp, equipped with clear inner and outer globes for curve *a* and with prismatic inner and clear outer globes for curve *b*.

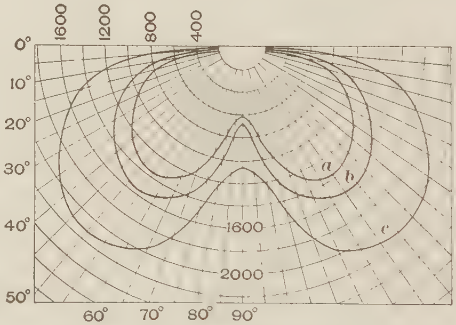


FIG. 32

57. The effect of impregnating the carbons with different light-producing minerals is shown in Fig. 32. An alternating-current lamp with different sets of carbons and with an input of 578 watts was used for all three curves. The white light, curve *a*, was produced at 1.202 watts per spherical candlepower; the red light, curve *b*, at 1.03 watts; and the yellow light, curve *c*, at .716 watt.

FEED-MECHANISMS

58. Open-flame carbon lamps with vertical electrodes have feed mechanisms very similar in principle to the unimpregnated carbon lamps. Three common types of feed-mechanism are in use with inclined carbon lamps; the *clock feed*, the *gravity feed*, and the *motor feed*.

59. In a **clock-feed lamp,** the carbons are suspended by a pair of chains wound over a drum driven by clockwork, or by one chain over the drum and an idler pulley, in such a way that both carbons are fed downwards at the same rate. The movement of the drum is regulated by a ratchet operated by the differential action of the shunt and series coils.

60. The main features of the **gravity-feed lamp** are shown in Fig. 33. The carbon holders are mechanically fastened together so that both must feed at the same rate, but the carbons can be drawn together or separated at the bottom in striking the arc. The negative carbon has along almost its entire length a projecting rib that rests on a support at the side of the economizer. As this rib is burned off, the carbons are gradually fed downwards. The carbons are in contact when the lamp is not burning, but are drawn apart by a single series coil as soon as the current is turned on, thus drawing the arc. The rib stops about 1½ inches from the end of the negative carbon; when the carbons burn down to this point, the negative drops out, and the arc is extinguished.

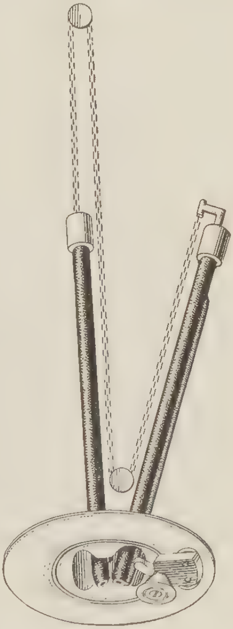


FIG. 33

61. The motor feed, possible with alternating-current lamps only, consists essentially of a series and a shunt magnet acting differentially on a rotatable disk, in which the alternating magnetism induces eddy currents. Induction by the series magnet causes rotation in a direction to separate the carbons, which are in contact when the lamp is out of service; induction by the shunt magnet balances the effect of the series magnet when the arc is of the proper length or overcomes it if the arc becomes too long.

CARE OF LAMPS

62. The same care in regard to polarity must be exercised in connecting direct-current flame arc lamps as is necessary with other direct-current lamps; otherwise, the light will be poor and the carbons will burn unevenly.

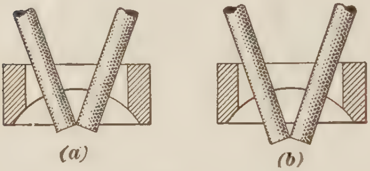


Fig. 34

When trimming an open-flame lamp, care should be taken that the carbons are left in the proper position. In a lamp in which the carbon holders are rigidly connected, as in gravity-feed lamps and in some clock-feed lamps, the carbons must be of exactly the same length, or the lamp will not operate properly. For best results, the ends of the electrodes should be central in the economizer when the lamp is burning; if too high or too low, the light is unsatisfactory, and adjustments are necessary. In a lamp with carbons that are cut square at the ends, the contact point should be just at the bottom of the economizer, as in Fig. 34 (*a*), for clock-feed lamps, and about $\frac{3}{8}$ inch lower, as in Fig. 34 (*b*), for motor-feed lamps. If the arc is allowed to burn too near the top of the economizer, the carbons are consumed too rapidly and the economizer may be destroyed. On gravity-feed lamps, the striking point cannot be adjusted.

METALLIC-FLAME LAMPS

ARC CHARACTERISTICS

63. Appearance.—In the **metallic-flame lamp,** also called the *magnetite lamp* or the *luminous-arc lamp*, for direct-current only, it is the arc flame proper that produces the light, rather than substances introduced into the arc stream and heated to incandescence thereby, as in the flame carbon lamp. Fig. 35 shows the characteristic shape of a luminous arc with the positive electrode above, and Fig. 36 that of a similar arc with the positive electrode below. In both cases, the intensely brilliant, bluish-white arc stream *a* is surrounded by a faintly yellowish flame *b* of heated solid particles from the electrodes, outside of which is a non-luminous envelope *c* of soot.

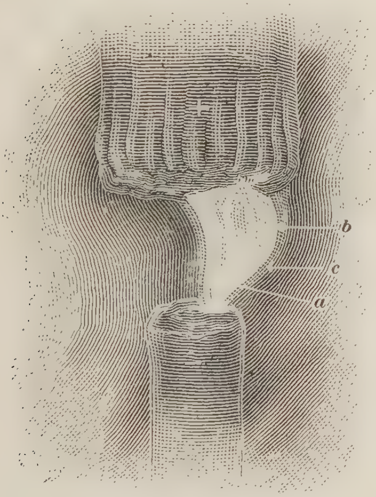


Fig. 35

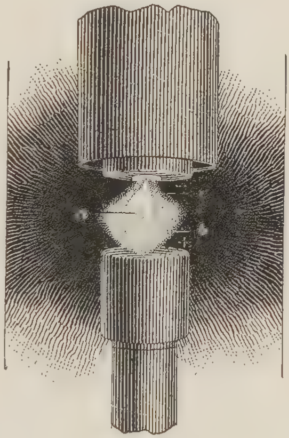


Fig. 36

Lamps are in standardized production by different manufacturers with the electrodes arranged in each of the two ways. In both of these types of lamp, the light comes almost entirely from the luminous arc itself. The arc is not, however, uniformly bright; but resembles a candle flame, having a bright and a non-luminous zone, the bright zone being near the negative electrode and consisting of a hollow cone-shaped mantle, as shown in Fig. 37. The luminous zone is brightest for about one-eighth of its length on the end next to the cathode, gradually diminishing in brilliancy as the anode is approached.

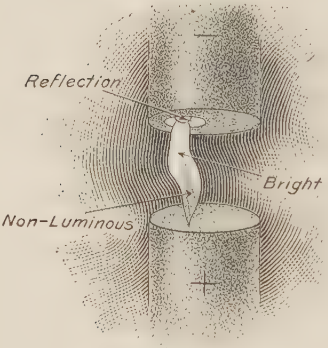


Fig. 37

64. Light Distribution. With the negative electrode uppermost, a broad distribution of light is obtained from the metallic-flame arc, as shown by curve *a*, Fig. 38, for a 6.6-ampere, 450-watt lamp. When the negative electrode is at the bottom, most of the light is thrown upwards, and a reflector is necessary. By suitably modifying the shape of this reflector, almost any desired distribution can be obtained.

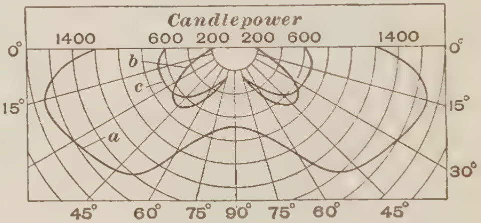


Fig. 38

For comparison with curve *a*, Fig. 38, the light distribution of a 6.6-ampere, 500-watt, series, direct-current, enclosed carbon arc lamp is shown by curve *b*, and that of a 4-ampere, 272-watt, series, direct-current, metallic flame arc lamp by curve *c*.

ELECTRODES

65. Magnetite, or black oxide of iron, is the best material known for the negative electrode of luminous-arc lamps. It is a good conductor; is practically unaffected by the air at any temperature; and produces a steady, though not brilliant, arc.

The iron furnishes the conducting vapor, which is rendered highly luminous by the addition of titanium oxide. A certain proportion of oxide of chromium also is added to reduce the rate of evaporation of the electrode.

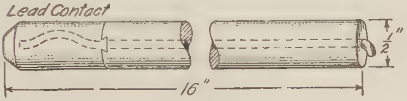


FIG. 39

Unless it reaches a temperature so high that its materials enter the arc by vaporization, as in the flame-carbon arc, the composition of the positive electrode has no effect on the character of the arc. It is usually made of copper or some alloy into a size large enough to radiate the heat without being rapidly destroyed.

66. The leading manufacturer of lamps having the anodes above makes the cathodes by packing the oxides solidly in a thin, sheet-iron tube, which serves to furnish mechanical rigidity and to assist in conducting the current. The material is loaded and packed in a *bumping machine*, by means of which a tube is repeatedly and slowly raised and then bumped on the base of the machine while the mixture is being slowly delivered. The cathodes are then thoroughly baked in an oven, the ends are sealed, and the iron sheath is coated with oil to prevent it from rusting. The life of the cathode is from 120 to 200 hours, varying with the size of the electrode and the current density.

The anode consists of a solid copper disk about twice the diameter of the cathode. Such an anode has a life of 3,000 to 4,000 hours.

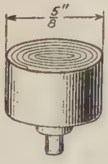


FIG. 40

67. The leading manufacturer of the type of lamp having the anode below makes the cathode in a manner quite similar to that employed for the ordinary carbon electrode. The materials are formed into a pasty mass, which is forced through a die, dried, and baked. A steel wire placed lengthwise through the middle of the electrode, as shown in Fig. 39, serves to carry the current. No sheet-iron containing tube is necessary for this electrode. Its life is from 175 to 300 hours, varying with different lamp capacities.

The anode for this lamp is composed of ribbons of copper and iron wound in a spiral and contained in an iron cup, as shown in Fig. 40. This anode is mounted on a cylindrical stem, made small to prevent the conducting of heat away from the electrode and thus to avoid cooling the arc. The stem is inserted in the lower terminal and both electrodes are replaced at each trim of the lamp, so that the lamp is always free from the effects of any previous run.

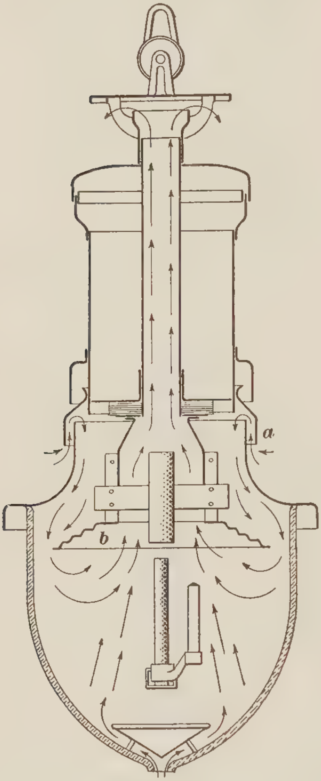


Fig. 41

VENTILATION

68. Good ventilation in metallic-flame lamps is of extreme importance. The scheme of ventilation in the standard lamp having the anode above is shown in Fig. 41. Air enters the lamp casing through an annular opening *a* and through a small opening in the bottom of the globe. From both openings the air-currents are directed along the inner surface of the globe, thus removing soot, whence they proceed upward under the reflector *b*, past the arc in the same direction as the arc flame, and up through the central chimney, which is tall enough to cause a strong draft. Most of the soot is carried up the chimney, but a small accumulation around the edges of the anode is removed by the automatic shaking of the anode during feeding and falls into a receptacle at the bottom of the globe.

The scheme of ventilation in the standard lamp having the cathode above is indicated in Fig. 42, which shows sections in two vertical planes at right angles to each other. Air enters through openings in the side of the casing and is directed downwards. One part passes through the enclosed arc chamber and downwards past the arc; the other part passes over the inner surface of the globe, keeping it clean. Both currents then join and pass up through the chimney.

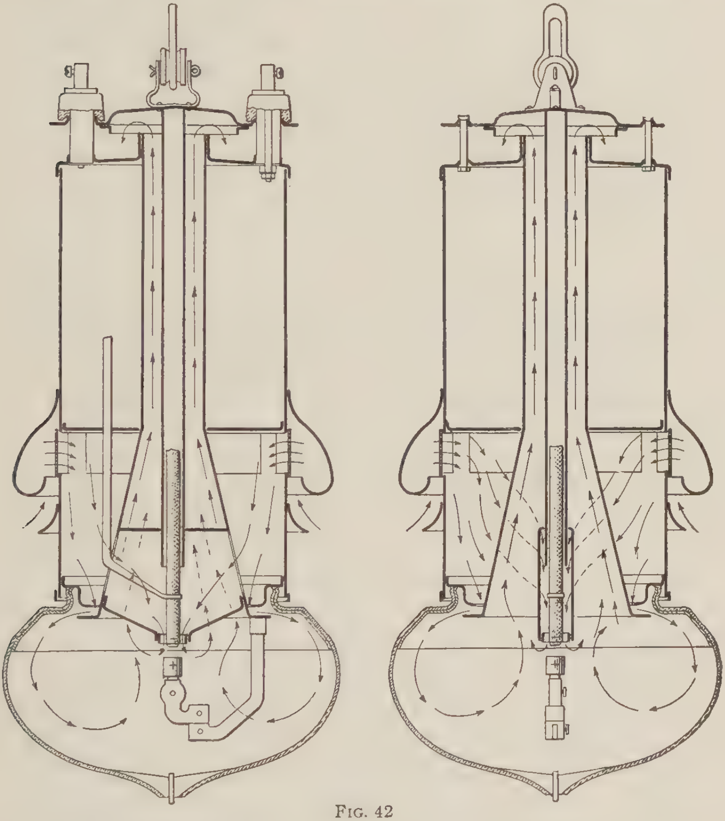


Fig. 42

In both Figs. 41 and 42, the feed-mechanism is omitted.

FEED-MECHANISMS

69. General Requirements.—The feed-mechanism of a metallic-flame arc differs from that of a carbon arc in that the electrodes must be separated when the arc is not burning.

Otherwise, since the arc is drawn between molten-metal surfaces, there is danger of the electrodes welding together when the current is discontinued; also, the slag that forms at the surfaces of the electrodes is not a good conductor when cold, and it is sometimes advisable to bring the electrodes together quite forcibly in order to insure satisfactory starting.

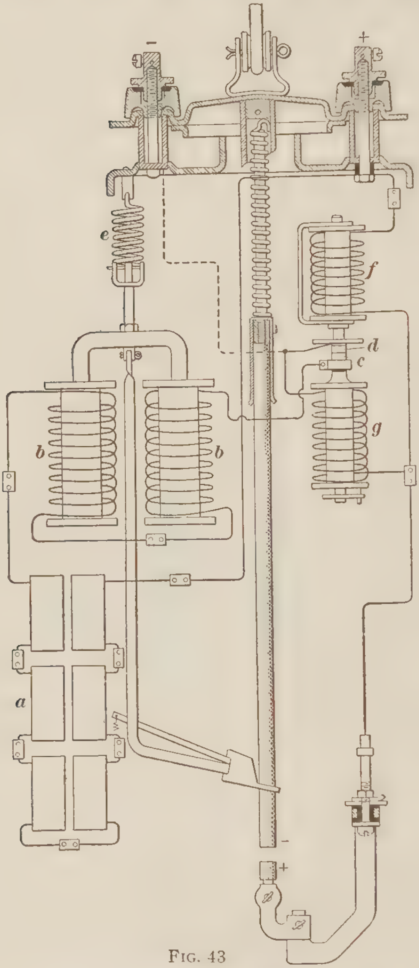


Fig. 43

The arc length must be mechanically fixed also, because the amount of light given off by a luminous arc is dependent on its length. Moreover, the length of a metallic-flame arc cannot readily be determined by either the current or the voltage. Hence, the only satisfactory system is to have the arc drawn to a definite length after each feed. This allows of a feed-mechanism of great simplicity, entirely free from floating parts.

The feed-mechanisms of both types of metallic-flame lamps are similar in principle, differing only in that the negative electrode must be fed up in one case and down in the other.

70. Series Lamps.—The principle of the feed-mechanism of a series metallic-flame lamp with the negative electrode above

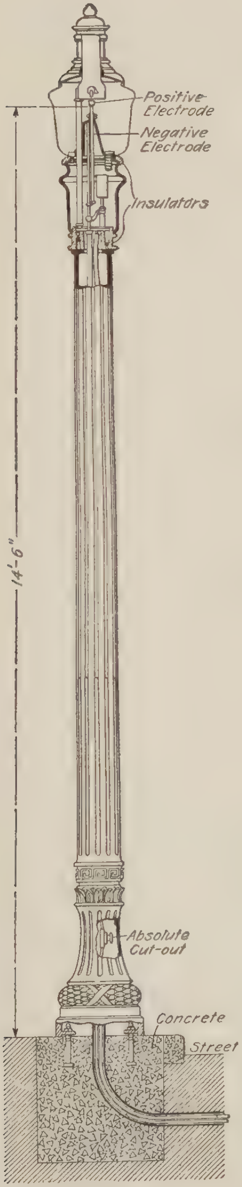


FIG. 44

is illustrated in Fig. 43. The starting current passes from the positive terminal through the starting resistance *a*, the feeding magnets *b*, and the contacts *c* and *d* to the negative terminal. The feeding magnets pull down on their armature, driving the electrodes together against the action of the spring *e* and completing a circuit through the series cut-out magnet *f*, which immediately separates the cut-out contacts *c* and *d*, opening the circuit through the feeding magnets, the armature of which is then pulled up by the spring, drawing the arc. As the electrodes burn away, the arc lengthens, increasing the voltage across the shunt cut-out magnet *g*. When this magnet becomes sufficiently energized to lift the contact *c* until it touches the contact *d*, the circuit through the feeding magnets is again closed, and the normal arc length is reestablished.

The operation of the feed-mechanism of the type of lamp with the negative electrode below is practically identical with that just described, except that the feeding magnets pull the electrode up instead of down, and act against the force of gravity instead of a spring.

71. Multiple and Multiple-Series Lamps.—The action of the multiple metallic-flame lamp is somewhat different from that of the series lamp, as it includes a rocker-arm with the magnetic pull of shunt magnets acting on one end and that of series magnets acting on the other end. The series magnets tend to lengthen the arc, and the shunt magnets to shorten it; with the proper arc voltage, the arm remains balanced.

The multiple-series mechanism is quite similar, except that resistors are automatically cut into circuit when the electrode burns out or when the lamp fails to feed for any cause. These resistors maintain the circuit and cause about the same voltage drop as occurs in the lamp when it is operating, thus keeping the other lamps in the series at the proper voltage.

ORNAMENTAL LUMINOUS-ARC LAMP

72. The **ornamental luminous-arc lamp** was designed to meet the demand for a post and lamp, in which the ornamental and advertising features are the predominating characteristics. The operating mechanism is placed below the arc and is enclosed in the hollow top of the ornamental post, which has the general appearance shown in Fig. 44. Provision is made for extra-long electrodes (15 to 18 inches). Except for its length and slightly smaller diameter, the electrode is exactly the same as in the regular luminous-arc lamp, and the operating mechanism is almost exactly the same. In the casing is provided a large door that gives ready access to the mechanism. The

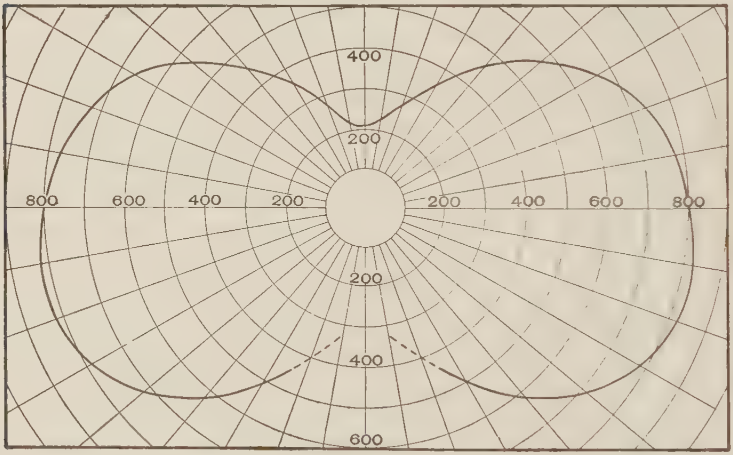


FIG. 45

current-carrying parts are highly insulated from the frame, and the lamp itself is insulated from the post. A cut-out in the base of the pole enables the lamp to be entirely disconnected from the circuit.

Owing to the rather special use to which this lamp is put, it is desirable that some of the light go upwards; hence, no reflector is used. The characteristic distribution is shown by the curve, Fig. 45. A special shape of alabaster globe is completely filled with light, no shadows appearing on the globe. The 6.6-ampere lamp consumes about 510 watts and has an efficiency of about .79 watt per mean spherical candlepower.

LONG-BURNING FLAME-ARC LAMPS

73. Advantages.—The metallic-flame arc lamp has the marked advantages of high efficiency and small maintenance expense; but its inability to operate on alternating current necessitates rectifying systems for series street-lighting circuits and entirely prevents its use on multiple systems where only alternating current is available. The open-flame carbon arc lamp, which can be made for operation on either direct or alternating current, has a maintenance cost so high that its use is impracticable except where the advantages of its remarkable illuminating qualities predominate over all other considerations. The evident need of an alternating-current lamp with advantages equal to those of the metallic-flame lamp led to the development of the **enclosed-flame carbon arc lamp,** with which a life of more than 100 hours per trim is secured by enclosing the arc and by using electrodes about $\frac{3}{4}$ inch in diameter. The arc voltage may be run anywhere between 40 and 80, depending only on the nature of the supply circuit, offering a striking contrast to the ordinary, non-flaming, enclosed carbon arc, with which satisfactory operation cannot be secured at less than 60 volts. Moreover, the enclosed-flame carbon arc has the high efficiency of the open-flame arc, while in the ordinary enclosed carbon arc the long electrode life is secured only by a considerable sacrifice in efficiency.

Roughly estimated, the comparative cost per lamp per year (4,000 hours) of trimming open-flame arc lamps as against enclosed-flame arc lamps is about as shown in Table I.

TABLE I

COMPARISON OF COST OF TRIMMING OPEN- AND ENCLOSED-FLAME ARC LAMPS

Item	Open-Flame Lamp	Enclosed-Flame Lamp
Hours life per trim	17	100
Number times trimmed per year	235	40
Number outer globes per year	½	½
Number inner globes per year	none	2
Cost, electrodes per trim	$.15	$.20
Cost, labor	.04	.04
Trimming Cost Per Lamp Per Year		
Cost, trimming, labor	$ 9.40	$ 1.60
Cost, carbons	35.25	8.00
Cost, outer globes at $.72	.36	.36
Cost, inner globes at $.25		.50
Total	$45.01	$10.46

74. General Features.—A steady arc is secured with the large carbons of the enclosed-flame lamp by carefully controlling the air-currents around the arc, and by using an arc from ½ to 1½ inches in length, depending on the arc voltage, the long arc serving also to give a comparatively large luminous area. An arc of large cross-section, that is, with large current, is much steadier than a smaller one; hence, a 10-ampere lamp is recommended whenever possible. In all direct-current flame carbon arcs arranged with vertical electrodes, the positive electrode is at the bottom, as it is much easier to feed the impregnating salts into the arc by this arrangement. In all flame-arc lamps it is found that those impregnating salts which produce a light of high efficiency tend also to make the arc unsteady, while those materials which give a steady arc have poor light-producing qualities. A compromise must always be effected, then, between high efficiency and steadiness of the arc.

The dense, white deposit caused by the condensation of the fumes from the arc is prevented by a careful arrangement of drafts from settling on the part of the globe that transmits the light, thus maintaining the efficiency throughout the life of the electrodes.

REGENERATIVE FLAME-ARC LAMPS

75. The **regenerative flame-arc lamp** makes repeated use of the chemical vapors that improve the light by circulating them repeatedly past the arc and through tubes or over surfaces where the white ash is condensed so as to interfere but little, or not at all, with the light. Proper circulation is obtained in the direct-current lamp with the negative electrode uppermost by the arrangement shown in Fig. 46. The arc is surrounded by a clear-glass cylinder *a* the ends of which are connected by two metallic condensing tubes *b* and *c*. The heat of the arc causes a strong upward current through the cylinder, and the vapors in passing down through the cooler tubes partly condense, leaving the white sediment inside the tubes, from which it is easily removed when trimming.

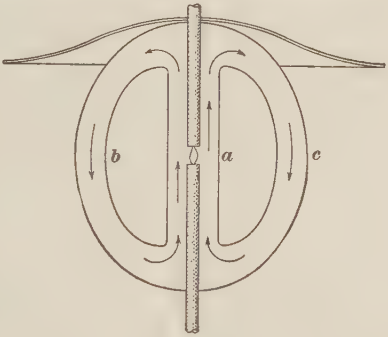


FIG. 46

A life of approximately 70 hours is obtained with a set of carbons and an arc voltage of about 80. A translucent outer globe surrounding the circulating tubes distributes the light so as to overcome largely the shadows cast by the condensing tubes. The maximum light intensity is about 3,400 candlepower at 40° below the horizontal, and the mean lower hemispherical candlepower 2,200. The input is approximately 550 watts, making the watts per candlepower .25.

MODERN ENCLOSED-FLAME CARBON ARC LAMPS

76. Draft Schemes.—The essential features of the draft schemes of later lamps employing the same general principles as the regenerative lamp are shown in Figs. 47 and 48. In both of these later lamps, the fumes circulate as shown by the arrows, and the white deposit condenses against the sheet-metal hoods *a*, leaving the glass globes free to transmit the light. The glass globe keeps much hotter than the walls of the condensing chamber, and remains practically free from deposits. The lamp shown in Fig. 48 has in the condensing chamber pieces *b* of magnesia or other substance with the property of absorbing some of the gases. In Fig. 48 many details of the lamp construction are omitted.

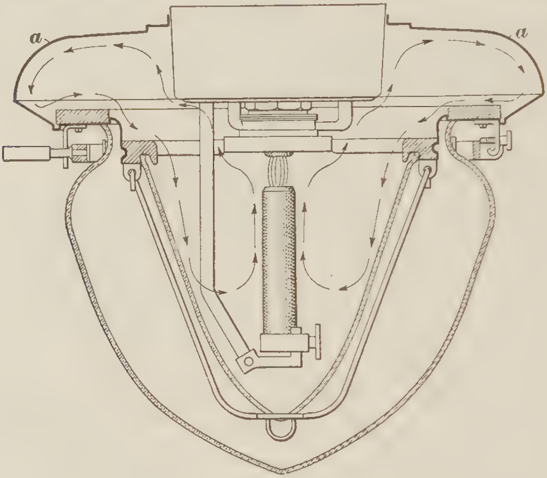


FIG. 47

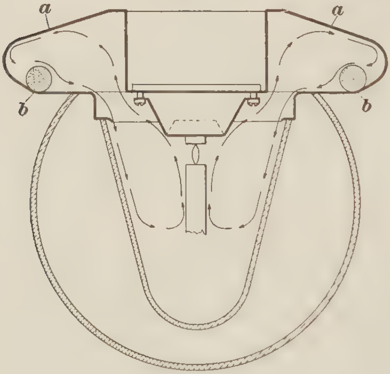


FIG. 48

It is advisable, though not absolutely necessary, to clean out the condensing chamber each time a lamp is trimmed, because the white deposit acts as a heat insulator and interferes somewhat with the proper condensation of the arc fumes.

Lamps of both these types are made for use on alternating- and direct-current circuits. In both, the arc is fully enclosed.

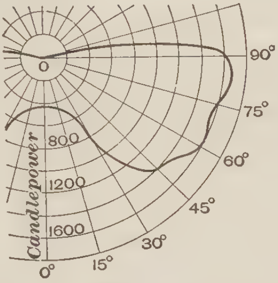


FIG. 49

77. Electrodes.—In the manufacture of electrodes for enclosed-flame lamps, the materials are mixed into a homogeneous paste, which is squirted through a die. The electrodes are then dried and carefully fired or baked. Electrodes are available giving golden-yellow light or white light, the latter being somewhat lower in efficiency.

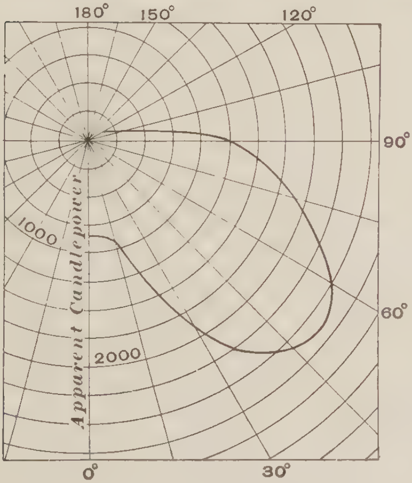


FIG. 50

78. Illumination. Typical distribution curves of the series, alternating-current, enclosed-flame lamps are shown in Figs. 49 and 50. The curve in Fig. 50 shows a maximum of nearly 2,650 candlepower at 40° below the horizontal, and a mean lower hemispherical candlepower of 2,019, at 10 amperes, with a consumption of 461 watts at 56 volts at the arc and 518 watts at 63 volts over the lamp terminals. The luminous efficiency, expressed in watts per mean lower hemispherical candlepower, is from .25 to .28 for alternating-current lamps, about .38 to .40 for direct-current multiple lamps, and .24 to .28 for direct-current, series, 10-ampere lamps.

FEED-MECHANISMS OF ENCLOSED FLAME LAMPS

79. Alternating-Current Series Lamp.—The feed-mechanism of an enclosed-flame arc lamp must be of the *focusing type* to feed both carbons at such a rate that the arc remains in an approximately fixed position. The principle of the focusing mechanism of one make of alternating-current series lamp is illustrated in Fig. 51. The upper and lower carbons are mechanically connected by chains over the double pulley *a b*, which is free to rotate about an axle borne by the rocker-arm *c*. The difference in the diameters of the two parts of the pulley compensates for the more rapid rate of consumption of the upper carbon, and keeps the arc at a nearly constant distance below the economizer *d*. When the lamp is out of service, the carbons are held together by gravity. The starting current energizes the series coil *e*, which swings the rocker-arm in a clockwise direction about its fulcrum *f* and starts the arc. As soon as the arc is started, the shunt magnet *g* begins to oppose the series magnet, and a balance is secured at normal arc length. As the carbons are consumed, the shunt magnet draws down its end of the rocker-arm, maintaining the arc length constant, until the clutch *h* reaches the releasing point. With the clutch released, the weight of the upper carbon causes the pulley to rotate about its axis, feeding the two carbons slowly together by gravity, independently of the rocker-arm, until the increased pull of the series magnet draws the rocker-arm far enough back to reengage the clutch. The gradual feeding of the carbons is commonly called a *sneak feed*. In the actual mechanism, to obtain

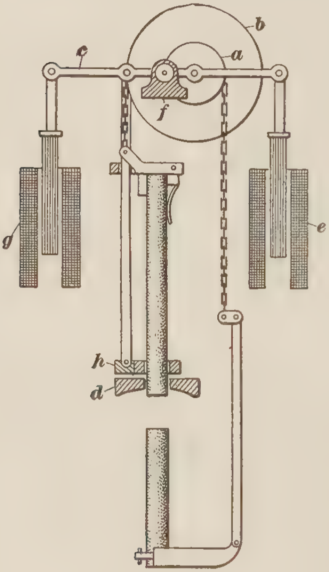


Fig. 51

mechanical balance, rigidity, and positive action, there are two double pulleys, two sets of chains, and two clutch rods arranged symmetrically and, in each case, acting as one.

Other mechanisms are in successful use, all designed with the same object in view—to keep the arc steady. In one mechanism, the clutch grips a machined surface on the chain pulley, thus insuring, even under severe vibration, the positive action required for the even, steady, sneak feed.

80. Alternating-Current Multiple Lamp.—A multiple alternating-current, flame-carbon lamp operates with a feed-mechanism very similar to that of the series lamp of the same make, except that the series coil is opposed by gravity only. An autotransformer is mounted in the top of the case to change the current from 6.6 amperes at 110 volts to 10 amperes at approximately 45 volts at the arc. Magnetic leakage makes the secondary voltage drop enough to provide ballast for the arc without resistance or additional reactance. This feature is particularly advantageous on account of the superior efficiency of the flame-carbon arc when operated at high current density.

Direct-current series and multiple mechanisms are similar to the corresponding alternating-current mechanisms; a series resistance is supplied in place of the autotransformer to reduce the voltage to that required at the arc and to provide ballast.

COMPARISON OF ARC LAMP CHARACTERISTICS

81. Table II gives average values of important characteristics of arc lamps in most common use in the United States. Individual lamps of any of the types listed may have characteristics differing somewhat from the values in the table. For example, the candlepower depends not only on the type of lamp, but also on the quality of the glassware and the electrodes, the voltage, the current regulation, the ventilation, the location of the arc in the arc chamber, etc. All values given in the table are based on most common practice.

SYSTEMS OF DISTRIBUTION FOR ARC LIGHTING

SERIES DISTRIBUTION

82. Characteristics of Series Circuits.—Most of the arc lamps used for scattered street-lighting work are connected in series. In Fig. 52, *A* represents a direct-current arc-lighting generator connected to arc lamps located at different points. The terminals of the lamps are marked + and − to distinguish them from each other. If the lamps are properly connected, the current in the circuit is in the direction indicated by the arrows. If one of the lamps should be connected backwards, as at *B*, the lower carbon would be positive and would rapidly burn away, possibly ruining the lower carbon holder. A lamp to be cut out of circuit is short-circuited by a switch, as at *s*.

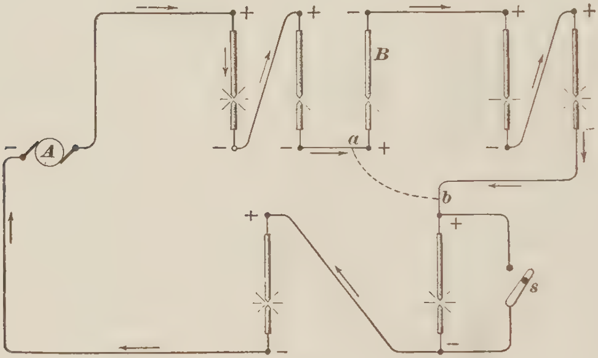


FIG. 52

In a simple series circuit, the current through all the lamps is the same unless there is leakage through the ground across a part of the circuit, as indicated by the dotted line *a b*. The current in the circuit must be kept constant, no matter how many lamps are in use; if each lamp requires 45 volts, the total voltage of the circuit must increase by 45 for every lamp added and decrease by the same amount for every lamp short-circuited. This change of voltage is accomplished by means of automatic regulators on the generators, or, when alternating current is used, by self-regulating, constant-current transformers.

The series system of distribution is about the only system that can be used economically where the lamps are scattered. Since the same current passes through all the lamps, the system is operated by using a small current (usually from 6 to 10 amperes) at a pressure depending on the number of lamps in circuit. The line-wire generally used is No. 6 B. & S. gauge, making the expenditure for copper comparatively small.

83. Types of Commercial Systems.—If the number of lamps in a series circuit is large, the voltage becomes very high. Thus, in order to operate seventy-five enclosed-arc lamps, requiring about 80 volts per lamp, including line drop, the machine must generate nearly 6,000 volts. Constant-current arc-lighting generators having a capacity of over 200 lamps in two or four circuits have been developed. These generators were not particularly efficient machines at best, and were troublesome to maintain in good operating condition. Moreover, the high-tension commutator was dangerous to adjust while in operation. For this reason, the direct-current enclosed-carbon lamp was quite generally superseded by the alternating-current lamp, fed from a constant-current regulator or transformer, connected as in Fig. 53 (*a*), in which *a* is a constant-potential alternating-current generator, *b* is a constant-current transformer, and the crosses represent lamps.

84. Alternating-current arc lighting systems have many advantages. The transformers can be made very efficient. The power can be generated in large, highly efficient, easily regulated alternators, which can be standard machines furnishing power to both constant-potential mains and constant-current arc-lighting systems. Standardization of station equipment is thus possible.

The regulator generally used in alternating-current, series systems is a transformer with a movable secondary coil, the position of which, relative to the primary, changes automatically with each change in the resistance of the secondary circuit. The number of lines of force included in the secondary is thus automatically adjusted so as to maintain the secondary current constant. This transformer is more completely described in another section.

Self-regulating choke coils were formerly used for constant-current regulation on alternating-current systems, and some of them are still in use. The position of a counterbalanced movable core in such a coil automatically changed with each change in the resistance of the circuit, thus changing the choking effect and maintaining the current practically constant.

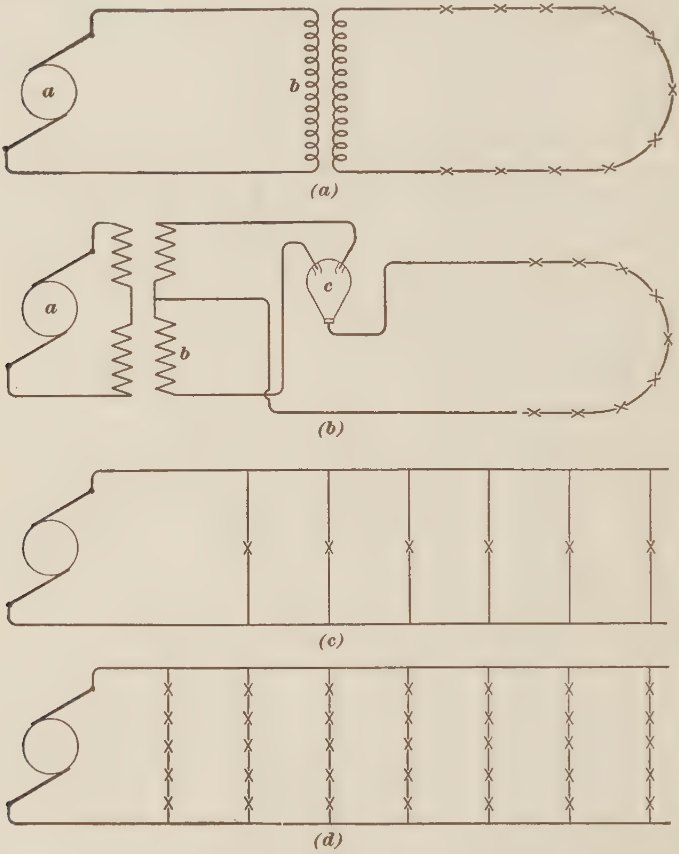


Fig. 53

When all the lamps are burning the regulation is good and the operation satisfactory; but with only a few lamps in circuit the power factor is very low.

85. Modern direct-current series arc lamps, such as the magnetite, are usually operated by rectified current from a constant-potential alternating-current system, as shown in Fig. 53 (*b*), in which *a* is a constant-potential alternating-current generator; *b*, a constant-current transformer; and *c*, a mercury rectifier. Such a system has the advantages of good regulation and high efficiency of the series alternating-current circuit, and is suitable for direct-current lamps.

PARALLEL DISTRIBUTION

86. Parallel distribution is the system in common use for incandescent lamps and motors; for arc lamps, the system is the same, as shown by Fig. 53 (*c*). As previously explained, the lamps themselves are, however, different from series lamps, chiefly on account of the necessity of ballasting resistance in direct-current lamps and choke coils or small transformers in alternating-current lamps. The arc voltage is about 75, while few circuits are operated at less than 110 volts. On 220-volt and 500-volt circuits, the loss in cutting the voltage down to 75 would be excessive, so from two to five lamps are operated in series across the line, as in Fig. 53 (*d*). In such cases, arrangements must be made for the automatic substitution of a resistance in place of any lamp that develops an open circuit, as, for instance, by the burning out of the carbons; otherwise, all the lamps in the same series, instead of only one, would go out. Short-circuiting the defective lamp, as is done on constant-current circuits, would not suffice, because the other lamps would then receive too high a voltage per lamp. The mechanisms of series-multiple lamps have been previously described.

TUBE LAMPS

MERCURY-VAPOR LAMPS

GENERAL PRINCIPLE

87. The characteristics of the mercury arc are fully explained in *Alternating-Current Rectifiers*. The **mercury-vapor lamp,** commonly called, after its inventor, the *Cooper-Hewitt lamp*, utilizes the mercury arc for light-giving purposes. The source of light is the arc stream itself, which operates at the lowest temperature of any known arc, from 200° to 250° C. The light-giving element *a*, Fig. 54, consists essentially of

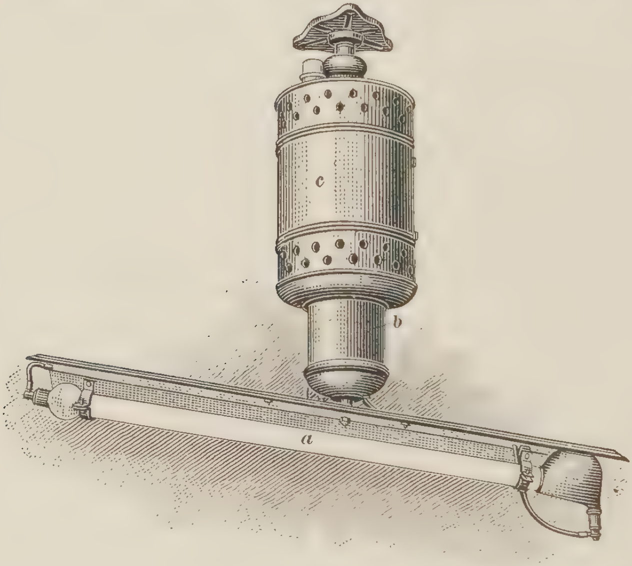


FIG. 54

a clear glass tube, in the walls of which are sealed platinum-wire terminals connecting with one or two iron anodes in one end and with a pool of mercury serving as the cathode in the other end. Air is exhausted from the tube, which is then hermetically sealed.

STARTING

88. A mercury-vapor arc can be started either by establishing current in a liquid-mercury path connecting the anode and cathode and then opening the path, or by applying a momentary starting voltage high enough to establish an arc through the rarefied mercury vapor always present in the tube.

89. The tube of a mercury-vapor lamp normally hangs in an inclined position, the mercury remaining in a bulb at the lower end. In starting an arc by opening a mercury path, the tube is tilted until the liquid mercury forms the path between the positive and negative electrodes, and is then allowed to fall back to its normal position after current is established. The tilting can be done by hand or by a magnet arranged to tilt the lamp automatically when the switch in the lamp circuit is closed. The appearance of a complete **self-tilting direct-current lamp** is shown in Fig. 54. The tilting mechanism is enclosed in the case at *b*.

90. The standard non-tilting lamp also starts automatically on closing its circuit switch. Over the cathode chamber of this lamp and in electrical connection with the positive electrode is a metallic coating, called the *starting band*, that, together with the cathode and the wall of the bulb, forms a condenser. The high, momentary starting voltage is obtained by means of inductance coils acting in combination with this condenser.

91. In order to steady the operation of a mercury-vapor lamp and to afford a means of adjusting the current, a resistor is connected in series with it. This and the inductance coils and other devices are compactly arranged in a case *c*, Fig. 54, and together constitute the *auxiliary*. A typical auxiliary for use with a **direct-current non-tilting lamp** is illustrated in Fig. 55, in which inductance coils are shown at *a*, the adjuster resistor is shown at *b*, and a device called a *shifter*, at *c*. The shifter is a small glass vessel containing mercury in a vacuum. When the lamp is out of circuit, the mercury bridges two contacts; but as soon as current is turned on, the shifter is automatically revolved by an armature attracted by the inductance coils, and the bridge is severed by a **V**-shaped indentation in the vessel, breaking the circuit through the inductance coils and thereby inducing between the lamp terminals a momentary voltage high enough to start the arc. To prevent the shifter from acting as a small mercury-vapor lamp there is connected in series with it a resistance *d*, that limits the current in the shifter circuit to a value so small that the shifter lights for a brief interval only.

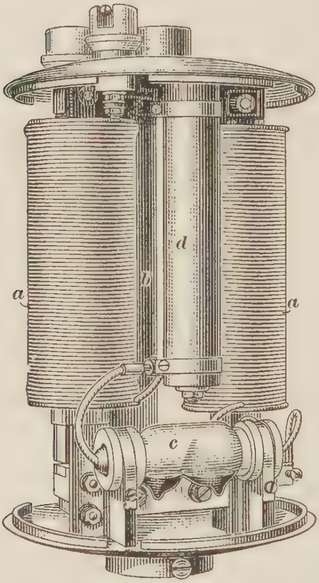


FIG. 55

ALTERNATING-CURRENT LAMP

92. As explained in connection with mercury-arc rectifiers, the cessation of a mercury arc even for an instant causes the restoration of the initial high cathode resistance, which must be overcome before the arc can be maintained by a comparatively low voltage. Alternating-current lamps are therefore provided with two positive electrodes and an autotransformer connected as shown in Fig. 56, so that current through the tube from one electrode begins before current from the other electrode ceases. The current in the tube is unidirectional, though fluctuating in value, and is prevented from falling to zero at the instant of reversal of the alternating line current by the inductance in series with the tube.

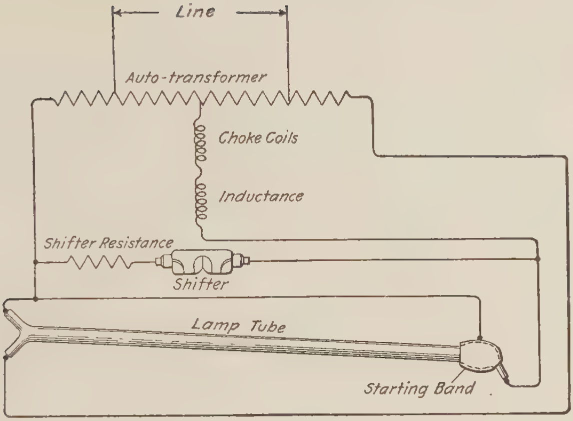


FIG. 56

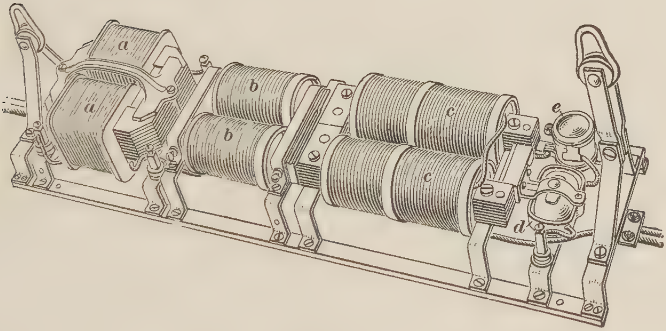


FIG. 57

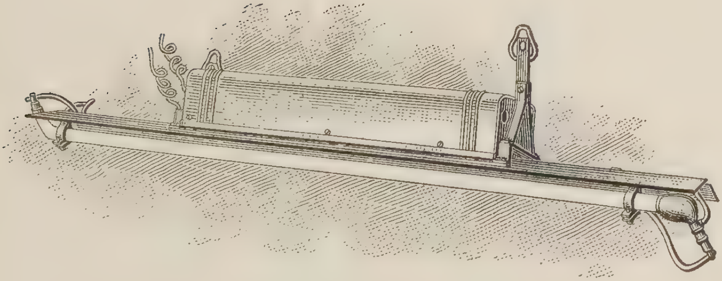


FIG. 58

The connections of Fig. 56 are those of a **non-tilting alternating-current lamp.** The arrangement of parts is shown in Fig. 57, in which the autotransformer is at *a*, the choke coils serving as ballast at *b*, the inductance coils for starting and for maintaining the arc during the reversals of the line-current at *c*, the shifter at *d*, and the shifter resistance at *e*. The appearance of the complete lamp is shown in Fig. 58.

OPERATION

93. Before starting a direct-current lamp, the polarity of the circuit should be verified with considerable care, as an attempt to start with the current in the wrong direction will melt the end of the negative leading-in wire, break the glass, and thus ruin the lamp.

In starting a hand-tilted lamp, close the switch, pull down on the chain until all the mercury has run from the cathode end to the anode end of the tube; then allow the tube to fall back slowly to its normal position. When the mercury forms a continuous stream between the electrodes, the current in the lamp is about double its normal value, and when the stream is broken, the tube at once becomes filled with a glow of light.

The automatic-tilting lamp should start promptly when the current is turned on; if it does not tilt or if it remains in a tilted position, the switch should be opened at once, or the starting-current may soon burn the lamp out. Search should then be made for the cause of the failure, usually sticking of the mechanism. Trouble in starting with any of the automatic-starting types of lamps can frequently be remedied by turning the current on and off several times in succession.

CHARACTERISTICS

94. The light given by a Cooper-Hewitt lamp is peculiar in that it contains no red or orange rays, but a great preponderance of green and purple rays, as well as ultra-violet rays. These last rays would, no doubt work considerable injury to the eye if they were not to a large extent filtered out by the glass of which the tube is made. The monochromatic (one-color) character of the light from these lamps tends to increase materially the acuity of vision; that is, it enables the eye to distinguish small objects and to define details more clearly than does ordinary sunlight, containing all the colors, or than does ordinary artificial light, containing a large amount of red or yellow rays. Red and orange rays are less effective in producing vision, and, owing to their heating power, are irritating and fatiguing to the retina; their absence, therefore, tends to make the mercury-vapor light easy on the eyes. Mercury-vapor light is worthless where colors are to be matched or distinguished.

Large luminous surface and low intrinsic brilliancy also tend to improve the illumination produced by mercury-vapor lamps; there is almost complete absence of glare, and no dense and sharply defined shadows are cast.

The light from an alternating-current mercury-vapor lamp fluctuates in a manner similar to that from an alternating-current carbon arc lamp; but at frequencies of 60 cycles per second and above, the effect is not noticeable, except on rapidly moving objects.

Mercury-vapor lamps operate successfully on voltages between 5 per cent. above and below the rated voltage, and will withstand momentary or periodical fluctuations between 10 per cent. above and 15 per cent. below the rated voltage. The operating characteristics of a typical alternating-current lamp are as follows:

Length of tube over all, in inches.......	55½
Length of tube light-giving, in inches...	50
Diameter of tube, in inches............	1
Candlepower.........................	670 to 850
Watts per candlepower................	.52 to .51
Power factor.........................	.50
Watts................................	350 to 430

COOPER-HEWITT LAMP REFLECTORS

95. Fig. 59 shows different forms of reflectors used with mercury-vapor lamps. The flat type is supplied where a medium distribution of light is desired; the curved type is used for concentrating most of the light immediately under the lamp; and the adjustable type permits almost any desired distribution to be obtained. With light-colored walls and ceiling, best results are obtained without the use of reflectors.

The large percentage of blue and purple rays in the light of the Cooper-Hewitt lamp makes it ideal for photographic purposes, as these rays form the so-called *actinic*, or *chemical, rays*, while the large luminous area produces the soft or diffused illumination so desirable for portrait work. In order to obtain still further diffusion and a sufficient volume of light to shorten the exposure, from four to eight tubes are usually mounted side by side in what is known as an **artificial skylight,** as shown in Fig. 60. The advantage of this skylight is that absolutely uniform results can be obtained at all times regardless of weather conditions; and these results can be made equal to the best work with daylight. The character of the mercury light

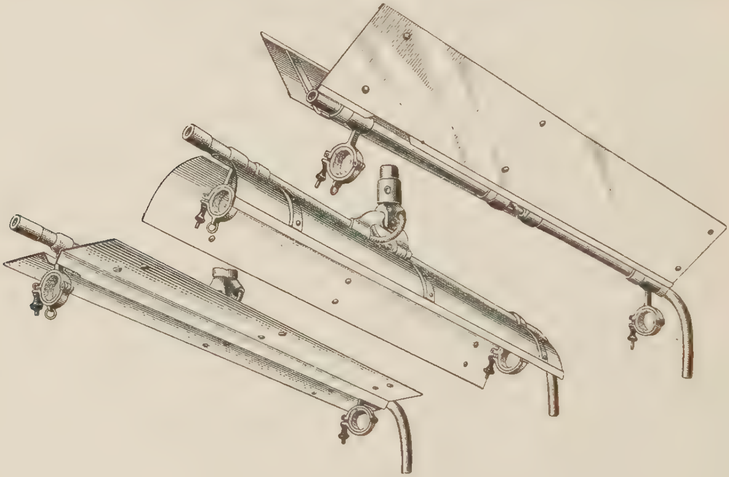


FIG. 59

is such, however, as to produce quite contrasty results unless special care is taken in the development. A similar equipment is also very useful for producing uniform light for enlarging and for making photographic prints and blueprints.

96. A **polarizing reflector** for use with mercury vapor lamps has surfaces coated with certain chemicals that introduce a certain amount of red and yellow into the light, so that colors can be distinguished. It is impossible to secure this result with ordinary reflectors; but, by virtue of the peculiar properties of the reflecting chemicals, the light is partly *polarized*—the strength of the blue and green light waves is reduced and the strength of the red and yellow waves increased. The peculiar characteristic color of the light from mercury vapor still predominates, but sufficient change is produced by polarization to make the lamps available for such places as express offices, for instance, where colored tags and lables must be distinguished.

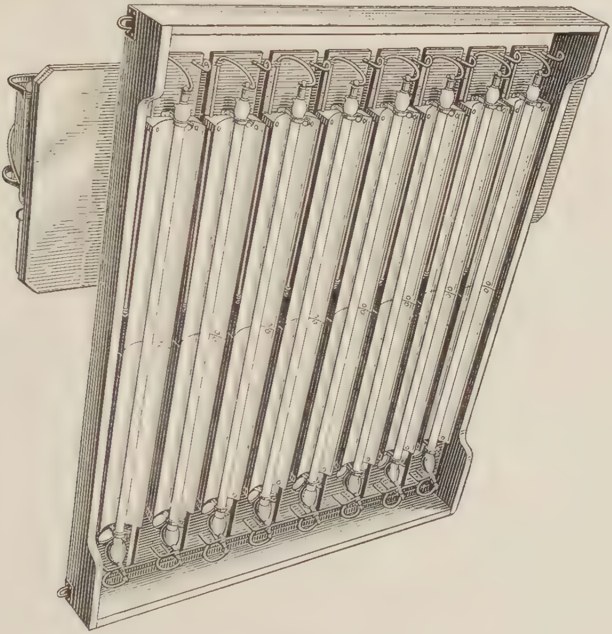


FIG. 60

THE QUARTZ LAMP

DESCRIPTION

97. Burner.—The **quartz lamp** is a modified mercury-vapor lamp operating at much higher vapor temperature and pressure and at higher efficiency than the ordinary mercury-vapor lamp. Quartz glass is necessary to withstand the high operating temperature; and the tubes are short, because the voltage drop per inch of tube is high at the high vapor pressure.

A type of quartz burner is shown in Fig. 61. In order to obtain sufficient cooling surface for the condensation of mercury vapor, the anode chamber *a* and the cathode chamber *b* are made relatively large. These chambers contain the mercury electrodes, which receive current through small sealed terminals. The tube is contracted at the joints with the electrode chamber, to regulate the mercury level and to prevent flickering of the arc. Then metal straps secure the tube to the reflector *c*.

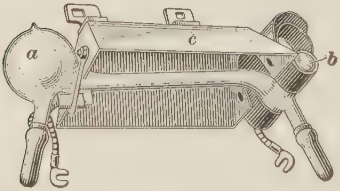


FIG. 61

98. Mechanism.—The operating mechanism of a quartz lamp designed for service on 110-volt constant-potential circuits is shown in Fig. 62. The quartz burner *a* differs from the 220-volt burner of Fig. 61 in that the luminous part is shorter and the leads to the electrodes are arranged differently. The burner holder is pivoted to a rigid support *b* and to the tilting lever *c*, which is linked to the movable armature of the electromagnet *d*. The burner, electromagnet, and two resistance coils *e* and *f* are connected in series. The burner in its normal position is inclined so that a path of mercury connects the two electrodes. When the line switch is closed, the electromagnet attracts its armature, and the burner is tilted until the mercury bridge breaks and the arc starts. As long as the lamp receives current the electromagnet holds the burner in its tilted operating position. A fuse mounted on the resistance coil *e* will carry the starting current for the brief period required for starting under normal conditions, but will be melted in about 1 minute by the abnormal heat from the coil if the mechanism sticks and the current continues. A small permanent magnet *g* engages the armature and prevents the operation of the tilting mechanism if the polarity of the lamp is reversed. A dashpot *h* dampens the movements of the mechanism. Fig. 63 shows the mechanism in perspective.

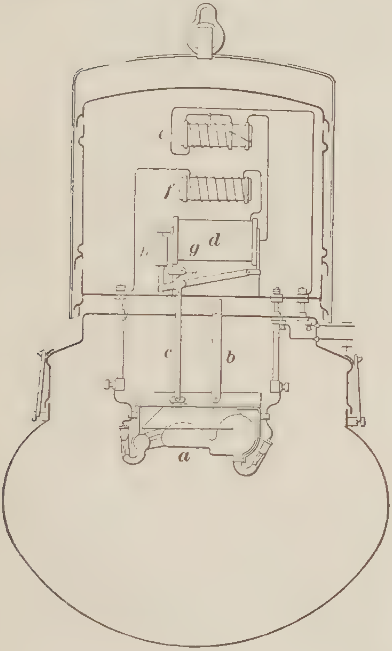


Fig. 62

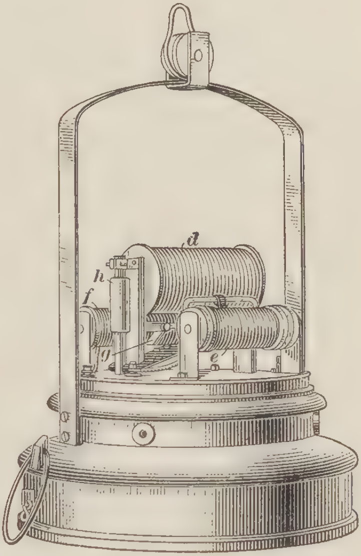


Fig. 63

99. In the normal position of the burner of the 220-volt lamp, there is no bridge of mercury between the electrodes; the bridge is formed by the tilting action of a shunt magnet, the circuit through which is immediately interrupted by a series inductance coil operating a cut-out, permitting the burner to tilt back and start the arc.

The mechanism of the 550-volt lamp is similar to that of the 220-volt lamp, except that the starting circuit contains an extra resistance to reduce the starting current, and a second inductance coil is added to compensate for the fluctuations of voltage on the usual commercial 550-volt circuit.

100. General Data.—Three prominent styles of quartz lamps, designed for multiple operation on 110-, 220-, and 550-volt direct-current circuits are manufactured in America. Table III contains miscellaneous data on these lamps.

TABLE III

QUARTZ-LAMP DATA

Characteristics	Style of Lamp		
	110-Volt	220-Volt	550-Volt
Supply voltage range	100–125	200–250	450–625
Average amperes	3.8	3.3	2.0
Maximum burner voltage	90	170	345
Candlepower, mean hemispherical, with clear glass globe	1,000	2,400	3,500
Commercial efficiency, watts per mean hemispherical candle, at nominal line voltage	.42	.30	.31

OPERATING CHARACTERISTICS

101. Starting Characteristics.—Owing to the heat-absorbing capacity of a quartz-lamp burner, the vapor pressure, which determines the voltage between the electrodes, does not increase immediately with the supply of energy to the burner. The pale, bluish-green color of the light when the cold lamp is first started indicates that the vapor pressure is very low. The starting current is limited, practically, by the series resistance only. As the burner becomes heated, the vapor pressure and burner voltage increase and the current decreases; stationary values are reached when the rates of heat absorption and dissipation at the electrodes have become constant. The starting characteristics of a 220-volt lamp are shown in Fig. 64.

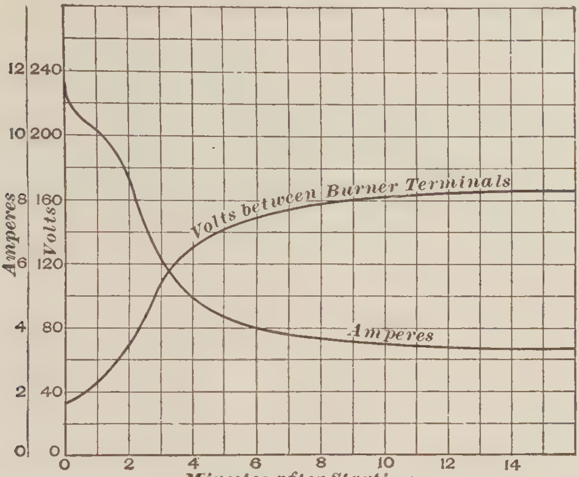


FIG. 64

102. Stationary Characteristics.—Even after stable operating conditions have been reached, the burner voltage of a quartz lamp does not respond immediately to a change in the supply of electrical energy; consequently, a sudden change in the line voltage causes a sudden change in the current. But, as the change in the supply of energy causes a change in the burner temperature and corresponding changes in the vapor pressure and burner voltage, the current gradually returns to the value it had before the change. At the higher vapor pressures, a change of 10 to 15 per cent. in voltage has very little effect on the current, as shown by the curve of Fig. 65. The current

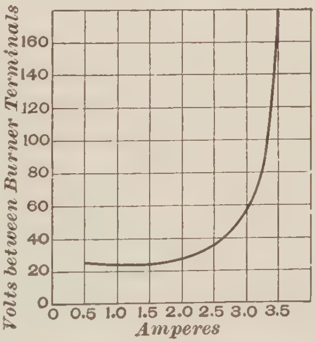


FIG. 65

remains practically constant unless some condition, such as ventilation, affecting the rate of heat escape from the vacuum container is altered; the final effect of a change in line voltage is a practically equal change in burner voltage.

COLOR OF LIGHT

103. In addition to the yellow, blue, green, and violet rays of the ordinary, or low-pressure, mercury-vapor light, the light from a quartz lamp contains red and orange rays in proportion to the temperature of the vapor. The physiologically injurious, though invisible, ultra-violet rays are also present and must be filtered out by surrounding the vacuum container with a glass globe, provided the lamp is to be used for general illumination. The light of a quartz lamp with a clear glass globe contains even fewer ultra-violet rays than sunlight. The abundance of ultra-violet rays makes the quartz lamp useful in certain chemical processes, for which purpose lamps with specially designed stands can be obtained.

MOORE LIGHTING TUBES

GENERAL DESCRIPTION

104. In the **Moore system of artificial lighting,** the source of light is the rarefied, non-metallic, gaseous contents of long glass tubes, made luminous by the passage of an electric current. The Moore tube can be made in many sizes and shapes, but usually it consists of a clear glass tube $1\frac{3}{4}$ inches in diameter and whatever length is desired up to 200 feet. The tube is usually placed near the ceiling, the two ends entering a small steel terminal box placed in any convenient location.

105. Theory.—If the difference of potential between two points, or terminals, in open air is gradually raised, sparks will finally jump from one terminal across the intervening air space to the other terminal, as shown in Fig. 66. The path of the discharge will not be a straight line, for the electricity will seek the path of least resistance, which includes particles of dust that may be floating in the air. The same tendency is seen when a lightning discharge passes in a zigzag path from cloud to cloud or from a cloud to the earth.

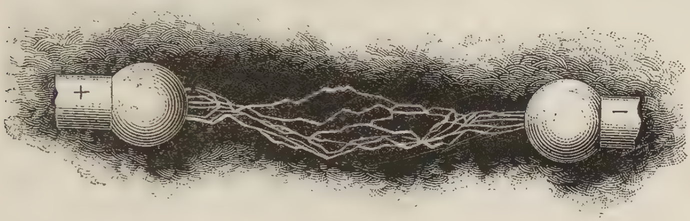


Fig. 66

If the two terminals are sealed in a glass tube and the air is gradually exhausted from the tube, a condition will soon be reached where the discharges, instead of following zigzag paths, as in open air, will become straight and continuous and will fill the tube with a glow of light. The electromotive force required to cause the discharge changes as the degree of exhaustion, or the pressure, of the air in the tube changes. At first the necessary electromotive force decreases rapidly as the pressure decreases, but a condition is soon reached where the electro-

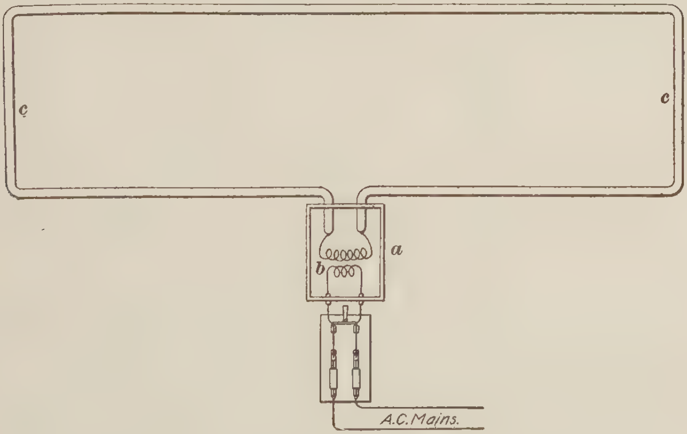


Fig. 67

motive force is a minimum. If the air pressure is further reduced, the electromotive force will have to be increased and the light will be less brilliant. For best results as a light source, therefore, the gases in the tube must be maintained at a definite pressure.

The color of the light when the tube contains only rarefied air is a rosy pink, but by introducing a suitable gas, the color can be made any shade desired; the light, in fact, can be made pure white. The coloring gas soon becomes exhausted and must be frequently renewed.

106. Connections.—In Fig. 67 are shown simplified connections of a Moore tube and in Fig. 68 more complete connections, including the regulator, to be described later. The voltages required to operate the tube are usually higher than is practicable with direct current. Low-voltage alternating current, such as is used for incandescent lighting, is led through fuses and a switch into a fireproof and danger-proof box *a* and through the low-tension coil of a step-up transformer *b*. The high-tension coil of the transformer terminates in carbon electrodes in the ends of the tube *c* inside the box. No wiring is necessary, except to bring the low-potential mains to the box, thus making the system very safe.

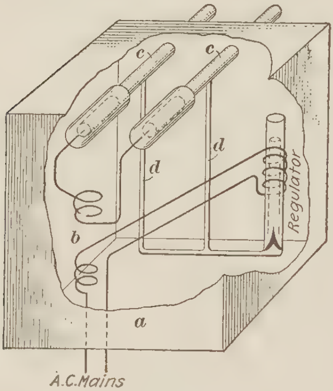


FIG. 68

When the main low-voltage switch is closed, the tube lights up immediately with a glow that can easily be regulated to any desired intensity from 2 to 25 or 30 candlepower per linear foot of tubing. The actual current passing through the tube, assuming that it is radiating 15 candlepower per foot, is about $\frac{1}{3}$ ampere, varying somewhat with the color of the light.

107. Vacuum Regulator.—Current in a Moore tube soon burns out the small quantity of air or gas needed to maintain the conductivity, and more gas in minute quantities must be admitted at intervals in order to keep the light at the maximum. The vacuum regulator is an ingenious breathing device by means of which the correct pressure is maintained in the tube. Its operation depends on the variation of the conductivity of the gas-column in the tube with varying gas pressure.

In Fig. 69 is shown a regulating feed-valve with a gas generator for supplying carbon-dioxide gas to the valve. The regulator consists of a valve operated by an electromagnet, the operating coil of which is connected in series with the low-voltage side of the transformer, as shown in Fig. 68. A porous carbon plug *a*, Fig. 69, is sealed into the bottom of a glass tube *b*, containing a small amount of mercury *c*. Into the mercury extends a movable tube *d*, the other end of which is attached to the core *e* of the magnet. As the degree of exhaustion in the lighting tube changes, the excitation of the magnet changes, and the core moves up or down, thus moving tube *d* up or down in the mercury. The surface of the mercury is thus lowered or raised.

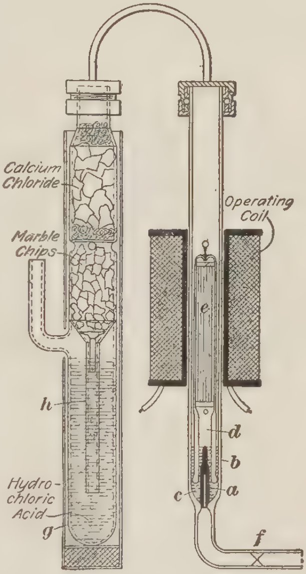


FIG. 69

Above the surface of the mercury is a space filled with carbon-dioxide gas, and when the tip of the carbon plug is exposed an extremely small quantity of the gas filters through the plug and passes into the lighting tube through tubes *d*, Fig. 68. By means of a stop-cock *f*, Fig. 69, the regulator can be shut off from the lighting tube. If the tube is fed with pure air, the light will be a rosy pink; if the air supply is first passed through phosphorus, the oxygen is withdrawn, leaving only nitrogen to enter the tube, and the light will then be yellow, which is the most economical color; or, as in this case, the tube can be fed with carbon-dioxide gas giving pure white light, the least economical color.

In operation, the valve acts about once a minute; as the pressure in the tube decreases, the current gradually rises until the carbon plug is exposed, allowing air or gas to enter; the current then gradually falls as the newly admitted gas diffuses through the tube, until the degree of exhaustion begins to increase again, thus working between fixed limits. No variation in the brilliancy of the tube can be detected, and in spite of the continual admission of new material, no change can be noticed except a deposit near the electrodes; and this deposit is very slight, even after long-continued use.

108. The carbon-dioxide gas is generated by the chemical action of hydrochloric acid on marble, or calcium carbonate. When the pressure in tube *b* becomes sufficiently reduced by the admission of gas to the lighting tube, atmospheric pressure causes the acid in the tube *g* to rise within the inner tube *h* and come into contact with the marble chips. The chemical action of the acid on the marble produces carbon dioxide. Thus, the feeding mechanism is entirely automatic. The marble pieces and the hydrochloric acid require renewal after the lamp has operated about 1,000 hours.

CHARACTERISTICS

109. Moore lighting tubes can be operated with alternating current at any of the frequencies ordinarily used for incandescent lighting. Direct current cannot be used, because with it high voltages are impracticable. If the supply current is direct, a motor-generator or a rotary converter must be used to transform it into alternating current.

The curves in Fig. 70 show characteristics of tubes of different lengths. For example, a tube 150 feet long at 12 hefners (10.8 candlepower) per foot requires 9,750 volts; the low-tension, or low-voltage, current input is 20.5 amperes; the power input, 2.9 kilowatts; and the watts per hefner 1.3, all these figures being approximate as read from the curves.

110. The **brilliancy** of the light from the Moore tube increases slightly during the first 100 hours of service; after that it remains fairly constant with constant voltage. The light output increases about in direct proportion to the increase in voltage, and the tube is not injured by a considerable variation of voltage. The greatest brilliancy at which the tube can be made to burn (about 30 candlepower per linear foot) is not great enough to strain the eyes when looking directly at the tube.

111. The **efficiency** of the tube also increases during the first 100 hours of service, but afterwards there is no apparent change during the life of the lamp, provided the voltage remains constant. Increased voltage causes not only increased brilliancy, but also increased efficiency. The efficiency of long tubes is greater than that of short ones, as shown by curve *d*, Fig. 70. By test, a tube 50 feet long consumed about 2.2 watts per candlepower; a tube 100 feet long 1.84 watts per candlepower; and a tube 150 feet long 1.5 watts per candlepower.

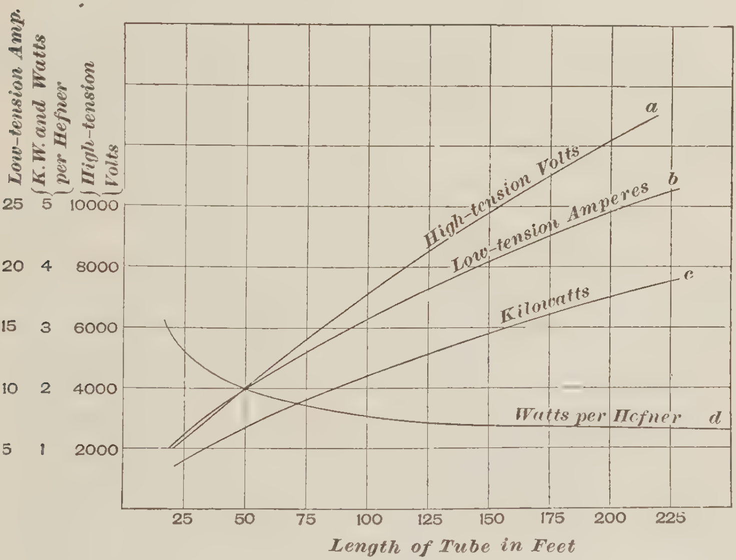


FIG. 70

Tests made on a tube 179 feet long that had been in use 1,000 hours showed a power consumption of 1.5 watts per candlepower at a brilliancy of 11.7 candlepower per foot of tube. This tube was giving an orange-tinted light; when producing white light, the efficiency is lower. The power consumptions here given include that of the transforming device.

112. Among the objections to the Moore tube are its low power factor—60 to 75 per cent.—caused by the necessity of either designing the transformer with very poor regulation or inserting an inductance to keep the arc steady, and the fact that the tubes can be used efficiently only in large units. In many installations the second objection is not serious, because the demand for large units, especially those having a distributed light source, is greater than that for small ones; the first may, perhaps, be largely removed with further developments.

APPLICATIONS

113. The Moore tube is well adapted for lighting any large interior. The color can be adjusted from golden yellow to what is virtually a white light that is peculiarly adapted to places where color selections must be made, as in stores where colored fabrics are displayed.

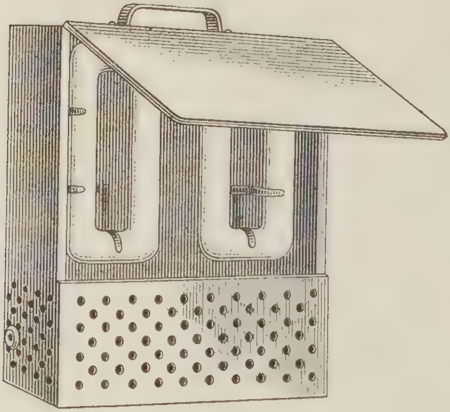


FIG. 71

The Moore light window, Fig. 71, is a small, portable unit with a tube only 6 feet long and consuming 400 watts. This unit is useful in textile mills and other establishments for testing colors. A tube installed in the entrance to a large public hall is shown in Fig. 72.

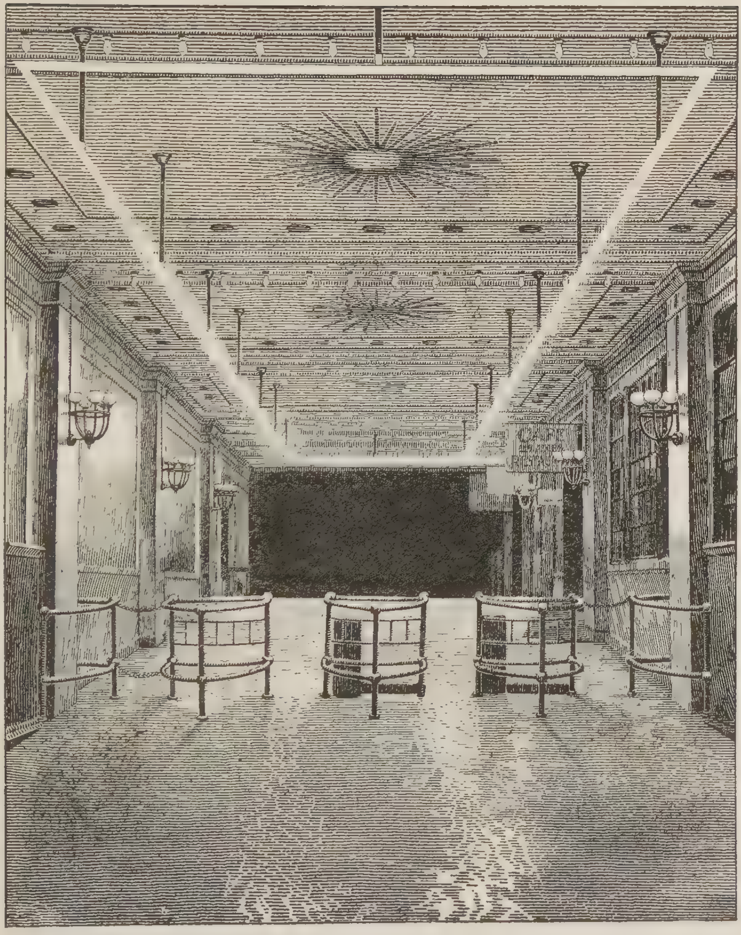


Fig. 72

ELECTRIC HEATING

INTRODUCTION

NATURE OF HEAT

1. The exact nature of heat is not known, but modern scientists generally agree that *heat is a form of energy due to molecular motion.* All matter, solid, liquid, or gaseous, is assumed to be composed of extremely small particles, called *molecules*, each in a continual state of rapid, but imperceptible, vibratory motion. When heat is applied to a body, the molecular vibrations increase in rapidity and amplitude, sometimes to such an extent that a solid is melted or a liquid vaporized. Conversely, upon sufficiently cooling a gas, its molecular vibrations may be decreased to such an extent that it is converted into a liquid, and eventually into a solid.

Heat, being a form of energy, may be produced in a body by the conversion of some other form of energy. The manner in which the flow of electricity through a conductor is converted into heat is not known; it is sufficient for the purpose of this Section, however, to assume that the heat is due to a kind of molecular friction.

TRANSMISSION OF HEAT

2. There are three distinct processes by which heat is transmitted from one place to another: *conduction*, *convection*, and *radiation*. Except between different parts of the same body, the transmission usually takes place by all three processes simultaneously.

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3. Conduction is the spreading of the molecular commotion in the hot part of a substance to the cooler parts.

If one end of a small iron rod is placed in a fire, the other end will soon become warm; heat has been conducted through it.

As a class, metals are the best conductors of heat; liquids and gases, the poorest. Organic substances, such as wood, felt, cork, paper, etc., are such poor conductors that they are classed as *heat insulators*. Most mineral substances, as rock, earth, glass, porcelain, mica, asbestos, etc., are also good heat insulators. Table I shows the relative conducting powers of common metals, silver being assumed to have a conductivity of 1.

TABLE I
HEAT CONDUCTIVITY OF METALS

Metal	Relative Conductivity	Metal	Relative Conductivity
Silver..........	1.000	Cast iron......	.170
Copper.........	.770	Zinc...........	.200
Brass...........	.330	Tin............	.150
Steel...........	.120	Lead..........	.085

4. Convection is the transfer of heat through a liquid or a gas by the motion of its particles. Generally, the motion is caused by the heat itself; thus, when a pail of water is placed on a stove, the particles at the bottom become heated, expand, and rise, giving up their heat, through contact, to colder particles. As the heated particles rise, other particles take their place at the bottom of the pail, and the process continues in an attempt to bring each particle to the same condition of temperature and weight. *Boiling* is simply rapid convection in which the particles at the bottom are converted into steam and rise quickly to the surface.

Gases and some liquids must be heated almost entirely by convection, and the heat, in such cases, may be applied with greatest effect at the bottom of the enclosure or container. It is impossible to heat a large pailful of water by applying heat at the upper surface.

5. Radiation is the process by which heat is transmitted from a hot body to a cold one through space that is entirely free from ordinary substance. Heat so transmitted is called *radiant heat.* A person attempting to warm himself at a blazing fire, outdoors on a cold day, may be scorched on one side by the radiant heat of the fire while he is almost frozen on the other side by the cold air that surrounds him. In the manner of its transmission, but not in its effect, radiant heat resembles light: both may be transmitted through a vacuum; both may be absorbed or reflected.

EMISSION, ABSORPTION, AND REFLECTION OF HEAT

6. A hot body suspended in air gives off heat to the air and to surrounding bodies by convection, by radiation, and, to a very slight extent, by conduction. The hot body is said to *emit* heat; the surrounding bodies, to *absorb* heat. The rate at which heat may be emitted from or absorbed at the surface of a body depends, among other things, on the kind of material and the condition of the surface, that is, whether it is rough, smooth, or polished. The absorptive and emissive powers of any given substance are usually equal. The relative amount of heat emitted or absorbed, under given conditions, at the surfaces of various substances is shown in Table II, which is

TABLE II

RELATIVE HEAT ABSORPTION OR EMISSION OF SUBSTANCES

Substance	Relative Absorption or Emission	Substance	Relative Absorption or Emission
Lampblack, dry	1.00	Steel	.17
White lead, dry powder	1.00	Polished brass	.07
Paper	.98	Polished copper	.07
Glass	.90	Polished silver	.03

based on an absorptive power of 1 for lampblack. The table indicates that the color does not affect the emissive or absorptive capacity, lampblack and white lead being equal in that respect.

7. The radiant heat that is intercepted by a body may not be entirely absorbed; part of it may be reflected. Table III shows the reflection, expressed as a percentage of the total radiant heat received, from various substances when the heat rays fall perpendicularly on them. The percentage of reflection varies with the angle at which the rays of heat strike the reflecting surface, becoming greater as the angle becomes less than 90°.

TABLE III

HEAT REFLECTING POWER OF VARIOUS SUBSTANCES

Substance	Reflection Per Cent.	Substance	Reflection Per Cent.
Polished silver......	97	Polished zinc.......	81
Polished brass......	93	Polished iron.......	77
Polished copper.....	93	Bright tin..........	85
Polished steel.......	83	Glass..............	10

The color of a surface also affects its heat-reflecting qualities, white or light-colored surfaces being better reflectors than those of dark colors.

DEFINITIONS AND UNITS

8. Temperature is the measure of intensity of heat; the higher the temperature of a body, the greater will be its ability to emit heat to other bodies at lower temperatures. As electromotive force may be said to be the measure of electrical pressure, temperature may be said to be the measure of thermal pressure.

Temperature values are commonly expressed in terms of the graduations of thermometer scales, which are arranged with reference to the freezing and boiling points of water at sea level. Several scales are employed, but those in general use are the

Fahrenheit (abbreviated *F.*) and the *centigrade* (abbreviated *C.*), both of which are explained in another Section.

TABLE IV

RELATIONS OF HEAT UNITS

1 joule	=.2389 therm	1 therm	=4.186 joules
	=.0002389 calorie		=.001163 watt-hr.
	=.000948 B. T. U.		=.00000116 K.-W.-hr.
1 watt-hour	=860 therms	1 calorie	=4,186 joules
	=.86 calorie		=1.163 watt-hr.
	=3.413 B. T. U.		=.001163 K.-W.-hr.
1 kilowatt-hour	=860,000 therms	1 B. T. U.	=1,055 joules
	=860 calories		=.293 watt-hr.
	=3,413 B. T. U.		=.000293 K.-W.-hr.

9. Units of Heat Quantity.—Quantity of heat is measured by the work performed in raising a body from one temperature to another. The units in which quantity of heat is expressed are taken up in a preceding Section. It is there explained that these units bear definite relations to other units of work, but for convenience these relations are again given in Table IV. The *kilogram-calorie* is used.

EXAMPLE.—(*a*) How many kilowatt-hours must be supplied to do the work of 6,000 British thermal units? (*b*) How many British thermal units have been furnished by a heating device of 100-per-cent. efficiency if the device has been run for 2 hours at 3 kilowatts?

SOLUTION.—(*a*) From Table IV, 1 B. T. U. = .000293 K.-W.-hr.; therefore, 6000 B. T. U. = 6,000 × .000293 = 1.758 K.-W.-hr. Ans.

(*b*) The work done in 2 hr. when the rate is 3 K. W. is $2 \times 3 = 6$ K.-W.-hr. From Table IV, 1 K.-W.-hr. = 3,413 B. T. U.; hence, 6 K.-W.-hr. = $6 \times 3{,}413 = 20{,}478$ B. T. U. Ans.

10. Specific Heat.—If equal weights of mercury and water are placed where they receive heat at the same rate, the temperature of the mercury will rise more rapidly than that of the water. Conversely, if both are heated to the same temperature, the mercury will cool quicker than water, when removed from the source of heat. Equal weights of different substances require different quantities of heat to cause a temperature rise of 1°.

Since heat units are based on unit weights of water the **specific heat** of a substance is the ratio between the amount of heat required to raise the temperature of the substance 1° and the amount of heat required to raise the temperature of the same weight of water 1°.

11. Latent Heat.—It can be shown by experiment that 142.65 British thermal units are necessary to convert a pound of ice at 32° F. into water at the same temperature. In other words, 142.65 British thermal units are required to melt 1 pound of ice. The heat necessary to change a solid into a liquid of the same temperature without raising the temperature of the solid is called the **latent heat of fusion** of the solid, and varies greatly with different materials.

To change a pound of water at 212° F. and at atmospheric pressure into steam at the same temperature and pressure requires 966 British thermal units. The heat necessary to change a liquid into a vapor at the same temperature and pressure is called the **latent heat of vaporization** of the liquid.

According to the molecular theory of heat, the quantity of heat necessary to change the state of a body is used in forcing its molecules farther apart. The latent heat is not lost, and always reappears when the body resumes its former state.

12. Thermal Resistance.—The resistance of a body to the flow of heat through it is frequently called its **thermal resistance,** which follows the same general law as electrical resistance, being directly proportional to the length of the conductor and inversely proportional to its cross-sectional area; thus, $R_t = s_t \frac{L}{A}$, in which s_t is the *thermal resistivity* of the substance. There is no name for the unit of thermal resistance nor for thermal resistivity, the latter being expressed as the reciprocal of *thermal conductivity*, the unit of which is expressed as heat units per degree per second per unit dimensions.

HEATING OF CONDUCTORS

GENERAL THEORY

13. In a conductor carrying a current of I amperes through R ohms of resistance, heat is generated at the rate of $I^2 R$ watts. This raises the temperature of the conductor until heat escapes to the surrounding medium (air or insulation) as fast as it is generated. If no heat can escape or if its escape is too slow, the temperature will continue to rise until the conductor or its insulation is ruined. Perfect heat insulation is impossible; but if the current is too large, the temperature will go beyond the safe limit.

The rate of heat production is easily determined when the current and the resistance are known. The rate of heat escape, or emission, depends on many widely varying conditions: the character of the surface of the conductor; whether the surface is bare or covered; the nature of the covering; the location of the conductor; and so forth. The escape of heat from a conductor under given conditions can be determined accurately by experiment only.

EMISSION OF HEAT FROM CONDUCTORS

14. Bare Conductors.—Heat escapes from the surface of a bare conductor by radiation and convection. The radiation is more rapid from a black or a dark-colored surface than from a bright one, and more rapid from a rough surface than from a smooth, polished surface. The convection is more rapid from a horizontal conductor than from a vertical conductor, and more rapid in moving air than in still air. Both the radiation and the convection increase approximately with the temperature elevation of the conductor above the surrounding air. A figure sometimes used in design calculations for combined radiation and natural (not forced) convection from black surfaces is .014 watt per square inch per degree centigrade.

15. Covered Conductors.—Although no two materials have the same thermal conductivity, good electric insulators are generally good heat insulators. Insulation alone will reduce the rate of heat dissipation from a wire of given temperature in air; but, since metals are good heat conductors, the lead sheath of a lead-covered cable suspended in air will actually aid in keeping the wire cool, on account of the increased radiating surface. In fact, insulated wire in wooden molding will often carry a given current at lower temperature than the same size of bright, bare wire in still air, because the thermal resistance of the insulation and the molding is less than that of air.

The heat from a lead-covered, insulated cable in an underground conduit escapes to the manholes partly by convection through the duct and partly by conduction through the material of the cable itself. The heat dissipated by the conduit ducts is relatively small.

The emission of heat from conductors embedded in an insulating mass, such as enamel, in rheostats, heating-devices, and so forth, depends on the area and character of the outside radiating surface and on the thickness and thermal conductivity of the insulation.

CURRENT-CARRYING CAPACITY OF CONDUCTORS

16. The **carrying capacity** of a conductor is the maximum current that it can carry continuously without causing a temperature rise high enough to injure the conductor or its insulation. The safe temperature limit depends on the properties of the conducting material and of the insulation. A conductor that corrodes rapidly when hot or that melts at a low temperature can be worked at only a low carrying capacity. The working temperature of a covered conductor is generally determined by the nature of the covering.

Since the carrying capacity depends on the rate of heat escape from a conductor, no general law covering all cases can be given; but, under the same conditions, the carrying capacities of two conductors of different materials will be inversely proportional to the square roots of their resistivities. The tables of carrying capacities given in other Sections are to a great extent the results of experiments.

FUSES

17. A **fuse** is a conductor designed to melt and open an electric circuit when the current reaches a value exceeding the safe carrying capacity of the weakest part of the circuit. The following are some of the principal requirements of a fuse:

It should melt at such a low temperature as not to ignite materials surrounding it. It should melt without spattering. It should have a definite melting temperature that will not change with prolonged heating at temperatures beneath the melting point. It should have terminals of some material sufficiently hard to insure good contact with the rest of the circuit. It should be long enough so that, after melting, an arc cannot be maintained between its terminals by the full voltage of the circuit.

To secure a low melting point, fuses are made of alloys varying in composition, but usually containing tin and lead, with other metals, such as bismuth, frequently added. Both *open fuses* and *enclosed fuses* are in use, the former having the fusible conductor exposed and the latter having it enclosed in some form of non-combustible tube or case.

The capacity of a fuse, or the current at which it will melt, depends on the material used, on the shape of the fuse, and on its installation, or, in brief, on anything that affects its melting point or the rate at which heat can escape from it. If a fuse of given material is so short that much of the heat escapes by conduction to the terminals, its capacity is increased. Installation in which there is good air circulation also increases the capacity. A fuse exposed to air oxidizes at continuous high temperatures below its melting point, and an open fuse may thus, in time, reach a capacity below that of an enclosed fuse of the same rating.

RESISTOR MATERIALS AND HEATING ELEMENTS

RESISTOR MATERIALS

PURPOSES, NATURE, AND REQUIREMENTS

18. The **resistor** of an electrical apparatus is the part that is purposely designed to oppose or limit the flow of electricity. The term *resistor* is synonymous with *resistance coil, resistance element, resistance unit,* and similar terms.

Most of the materials used for resistors, and especially those used for heating appliances, are made of metallic alloys of either secret or patented composition. Carbon usually enters into the composition of resistor materials other than alloys, the carbon being combined with some other material that renders the compound practically non-oxidizable.

19. The chief quality required of the resistor material for a heating appliance is that it withstand the maximum desired temperature without deterioration; it should not scale, oxidize, nor become brittle. The material should be capable of being made up in different shapes to adapt it to different uses. It should be of as low specific gravity as possible in order to keep down the weight of devices in which it is used. The structure of such material should be homogeneous, so that its resistance will be uniform. If the resistor material is a metal, it should be malleable and ductile, yet tough, and its coefficient of expansion should be small so that it will not alter appreciably in size with increase in temperature. The material should have a low temperature coefficient of resistivity, so that the resistance of a given resistor will not change greatly through a considerable range of temperatures. It should have good current carrying capacity, because the maximum heat obtainable from two conductors of equal resistance is directly proportional to the squares of the maximum currents that the respective conductors can carry. The melting point must be high to permit high temperatures.

METALLIC RESISTORS

20. Resistor materials for heating appliances of relatively small capacities are usually alloys. The properties of some of these are listed in Table V. The values given in the second and third columns are only approximate. Each of these alloys is claimed to be practically non-oxidizable at the working temperature; but unless protected from the atmosphere by a coating of enamel, or otherwise, deterioration will slowly take place.

TABLE V

PROPERTIES OF RESISTANCE ALLOYS

Material	Working Temperature Degrees F.	Melting Point Degrees F.	Resistivity Ohms per Circular-Mil.-Foot	Temperature Coefficient of Resistivity per Degree F.	Weight in Pounds per Cubic Inch
Calorite	1,200	2,660	560–700	.000106	.300
Excello resistance metal	1,200–1,400	2,730	550 (at 60° F.)	.00009	.320
Superior resistance metal	1,000	2,500	525 (at 60° F.)	.00045	.290
Nichrome	2,200	2,800	600 (at 75° F.)	.00024	.294
Nichrome II	2,000	2,800–3,000	660 (at 75° F.)	.00009	.290

NON-METALLIC RESISTORS

21. Silundum is an electric-furnace product obtained by heating carbon in a vapor of silicon. Silundum is therefore a carbide of silicon with the same general properties as the familiar abrasive, carborundum. It can be made in any shape in which carbon can be formed; it is very hard; it resists temperatures up to about 1,600° C. without oxidation in air. The electric resistance of silundum is variable, depending on the nature and hardness of the carbon entering into the compound. Silundum made from porous carbon has a higher resistance than that made from hard, dense carbon. Relatively, however, the resistance of silundum is several times that of carbon. Like carbon, silundum is a very refractory material and does not melt, but the silicon is driven out of the compound at a temperature of about 1,700° C.

22. Kryptol is the trade name of a patented granular resistance material composed of carbon and some inorganic substance to prevent the carbon from burning. It is used chiefly in some types of small electric furnaces; its granular form renders it unsuitable for some purposes of electric heating. A resistor of kryptol varies in resistance according to the size of the grains and to how tightly they are packed, because much of the resistance is at the points of contact among the grains. Other conditions remaining the same, tight packing reduces the resistance.

23. Helion is the name given to an invention originally intended to be used as an incandescent-lamp filament; but its properties render helion more suitable for some kinds of heating devices, and such devices are being produced commercially. Helion is made by subjecting a core of carbon to a process resembling the flashing process of the carbon-filament lamp. Instead, however, of the usual hydrocarbon of the ordinary flashing process, a volatile compound of silicon is used. The carbon core thus acquires a metallic deposit, producing a material of peculiar properties. The specific resistance of helion is about fifty times that of the ordinary carbon filament. The temperature coefficient is at first negative, but becomes positive at a temperature of about 1,375° C., remaining positive until a temperature of about 1,800° C. is attained, when it again becomes negative. At 1,800° C., helion filaments become brightly incandescent, and the efficiency of operation is apparently a maximum at this temperature.

Great strength and durability are claimed for helion. It is claimed that an incandescent helion filament may be plunged into water without injury. When burned in open air, a helion filament is, to some extent, affected by a deposit of dust fusing to the surface, thus shortening the life of the filament. Helion, owing to its high resistivity, permits the making of filaments of much larger cross-section than the ordinary carbon filaments, thus adapting it to use in heating devices. Its high resistivity also gives helion a certain advantage over metallic alloys, in that a short length of helion has the same resistance as a much longer piece of metallic resistor of the same cross-section. Some difficulty is, however, experienced in providing suitable terminals for helion resistors.

HEATING ELEMENTS

CLASSIFICATION AND APPLICATION

24. The **heating element,** or *heating unit,* of an electric heating device usually consists of some form of resistor properly mounted and provided with means for connecting it in an electric circuit. Heating units are of two fundamental types, the *open type* and the *enclosed type.*

The **open type** of heating element, in which the resistor is exposed to the air, is divided into two classes, the *luminous* and the *non-luminous.* **Luminous units** are worked at glowing heat, and are sometimes called *glowing* or *radiant* units. They are applicable where high temperatures are needed in restricted space. **Non-luminous elements** are worked below the glowing point, and are generally used for heating comparatively large volumes of air through small temperature ranges.

In **enclosed heating elements,** the resistor is surrounded by a material with good electrical and heat-resisting properties and thoroughly insulated thermally except at the surface where the heat is intended to escape. The names *encased units* and *armored units* are also applied to such units. They are usually worked at temperatures below red heat.

In all heating elements, regardless of class or type, the resistor should form a non-inductive path for the current, unless the element is to be used on direct current exclusively.

EXAMPLES OF HEATING ELEMENTS

25. One type of **open-coil heaters** is illustrated in the old-fashioned car heater shown in Fig. 1. The resistance wire is wound in a long helix with a cord *a* of asbestos. The helix is looped over porcelain insulators attached to opposite sides of steel strips *b*. This style of heater is unsuitable for alternating current on account of the high self-induction of such a winding. Many other types of air heaters are in use for electric-car heating. Such heaters must necessarily be worked considerably below red heat. They are designed to cause a temperature rise of 40° to 60° F. in relatively large volumes of air under conditions of fairly good circulation.

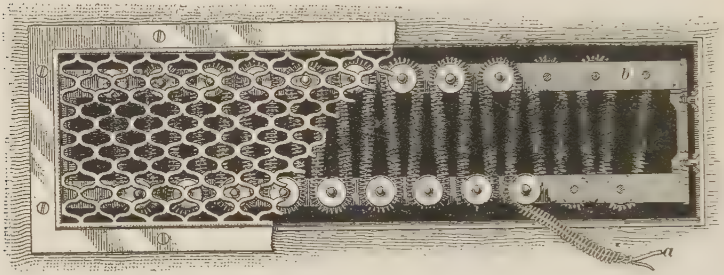


FIG. 1

26. A **radiant open-coil unit** as adapted to an electric range is shown in Fig. 2. The circular base and the removable, grooved brick that holds the coils are made of special composition resembling porcelain. The resistor consists of ten helical coils, one coil per groove, of practically non-oxidizable metal, connected in parallel. Each coil can be removed without interfering with the others.

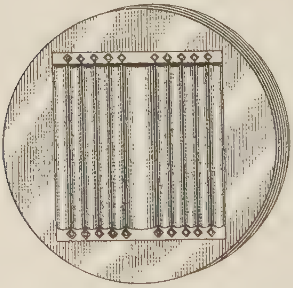


FIG. 2

27. An **encased disk unit** used chiefly as a hot-plate for domestic utensils is shown in Fig. 3. In some of these units the resistor is made of calorite ribbon wound around a thin disk of mica as in Fig. 4, in which *a* and *b* indicate the resistor terminals. In others, the resistor is made in the form of a grid by punching out a very thin sheet of the resistance metal. In either case, the resistor is encased and clamped between thin metal plates from which it is insulated by mica. The encased resistor is then mounted on a heat-insulating compound, or cement, in which the connections are embedded and by which the terminals are supported.

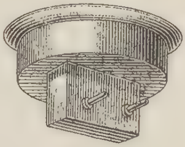


Fig. 3

28. A **spiral unit** is formed by arranging a continuous coil of resistance wire in the form of a spiral. These units are usually applied to heating flat surfaces larger than 6 inches in diameter. In some types of heaters, the unit is a helical coil laid spirally in a pan, a continuous strip of mica separating adjacent turns and a layer of mica or quartz enamel separating the unit from the heating surface. The arrangement of a spiral disk unit is shown in Fig. 5.

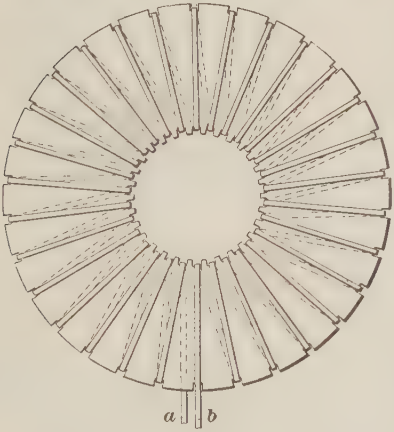


Fig. 4

29. The **Prometheus heating units,** an example of which is shown in Fig. 6, are composed of very thin strips of mica on which is painted a film of non-oxidizable metal, such as platinum or gold, sometimes so thin as to be quite transparent. It is applied by mixing the powdered metal with a suitable flux and then painting it on the mica, after which it is subjected to a high temperature. To prevent injury to the film, it is covered with another strip of mica, and then totally or partly enclosed in a thin metal frame. With this system of construction it is possible to make units in almost any desired form.

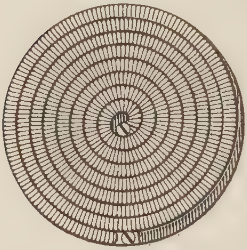


FIG. 5

30. A resistance composed of iron strip, or ribbon, with deep, narrow notches punched in the edges, is shown in Fig. 7. This ribbon is first insulated by a wrapping of mica, and is then laid in molds, where the metal of the heating device is cast around it, thus making the resistance unit an integral part of the heater.

31. An armored heating element, known as a **cartridge unit,** is made by winding flat resistance ribbon edgewise in the form of a helix on an arbor and then binding the turns together and at the same time insulating them from one another by a heat-resisting cement or enamel. The unit is thus formed into a solid tube, which is then wrapped in a thin sheet of mica and enclosed in a thin metal shell. In cartridge units designed for 110-volt circuits German silver is used; for 220-volt units, calorite is used. Appliances designed for these units have chambers bored to receive the cartridges with a close fit. A cartridge unit is illustrated in Fig. 8.

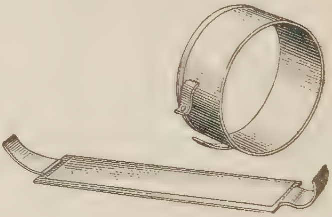


FIG. 6

32. An **enamel heating element** is one in which the resistor is permanently embedded, or sealed, in enamel. This enamel resembles porcelain enamel such as is used for enameled ironware and consists of two parts, a ground body and a surface.

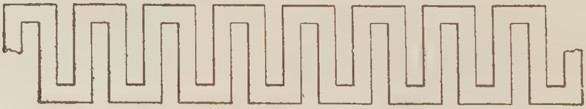


FIG. 7

In the usual method of construction, the ground enamel is laid next to the heating surface, the resistor being then laid on this in the correct position, and finally the surface enamel is fired on. In order to get a long resistor into the small area of the heating element, the wire or strip is crimped or zigzagged. Lugs are fixed to the ends of the resistor in order that connection may be made easily when the element is complete.

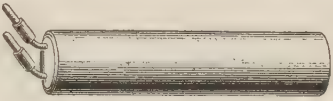


FIG. 8

Enamel elements are made in many forms, depending on the uses or utensils to which they are to be adapted. For domestic appliances, the heater is usually made into the form of a cast- or a wrought-iron disk. For radiators designed for air heating, the iron heating surface is increased by corrugations, nurls, or ribs.

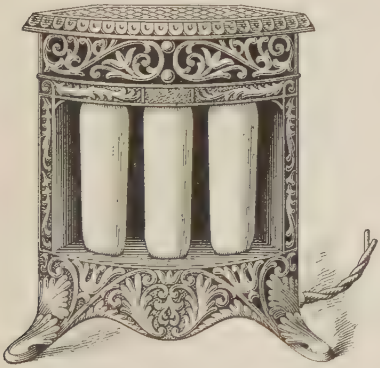


FIG. 9

33. Between 95 and 100 per cent. of the energy expended in incandescent filament lamps is converted into heat. This fact is utilized in the **radiant bulb unit,** which is merely a modified form of the incandescent lamp. The bulbs are usually frosted to obviate the glare from the filament. This unit is used in luminous electric radiators only, two or more bulbs per radiator being employed, depending on the amount of heat desired. A three-bulb radiator is shown in Fig. 9. Luminous radiators are designed for temporary use as an auxiliary to the regular heating system of a dwelling house.

COMMERCIAL APPLICATION OF ELECTRIC HEAT

USE, ADVANTAGES, AND COST

34. Heat from electrical energy may be used wherever heat from any other source may be utilized. The great drawback to the use of electricity for general heating purposes is its expense. There are, however, many instances where the high cost of electric heating is offset by its convenience. There are also certain industrial products, such as carborundum, which can be produced only at the high temperature of the electric-arc furnace. Most of the applications of electric heat, however, are in those places where the heat is localized and used only intermittently.

35. **Advantages of Electric Heat.**—Some of the advantages of electric heat are as follows: (1) Its instant availability on closing a switch; (2) its perfect control, as heat may be obtained by its use in almost any intensity desired; (3) its perfect adaptability, as it may be applied to the exact location desired and in such a way that only very little heat escapes to the surrounding air or other objects; (4) the absence of smoke, flame, dust, poisonous gases, etc.; (5) the absence of fuel, ashes, etc. to be handled, or fires to be maintained; (6) the decreased danger from fire or explosions.

36. **Cost of Electric Heat.**—A comparison of costs of electric heat for any purpose with heat from other sources can be made only by careful observation of results obtained over a considerable period of time. Experiments in household cooking seem to show that to compete with gas at $1 per thousand cubic feet, electric energy should be obtained for about $2\frac{1}{2}$ cents per kilowatt-hour; and to compete with coal at from $6 to $7.50 per long ton, the cost of electricity should not be greater than 4 or 5 cents per kilowatt-hour.

Unless the efficiency of utilization is properly taken into account, it is sometimes misleading to compare heat from electricity with heat from other sources, especially if a small amount of heat is required intermittently for short periods only, as for heating flat irons. In addition to being economical of heat, the electric iron is always at the right temperature, thus saving time in the work itself and entirely eliminating the walking to and from the stove; therefore, when the cost of ironing a certain amount of clothes, instead of the cost of energy per heat unit, is taken as a measure of economy, the electric heat will probably be found the cheaper.

HEATING OF ROOMS

37. The quantity of heat required to raise the temperature of a volume of air, as in a room or an oven, depends on the shape of the air space, the nature of the enclosing walls, the ventilation, and the atmospheric conditions outside the enclosure. To maintain the desired temperature after it has been reached, the heat losses through conduction and ventilation must be supplied. In well-constructed houses, the loss of heat by conduction is so small in comparison to the loss by ventilation that the former may be neglected. In rough estimates, the shape of the room also may be neglected, and no allowance need be made for heat supplied by artificial lights or by the bodies of occupants of the room.

38. Room-Heating Estimates.—It requires an expenditure of 18 joules to raise the temperature of 1 cubic foot of air 1° F. Assume V cubic feet to be the volume of a room in which the air is changing at the rate of v cubic feet per minute. It is desired to secure in T minutes a rise of t° F. in the temperature and to maintain the temperature elevation thus secured. It will require 18 $V\,t$ joules to bring about a temperature rise of t° in V cubic feet of still air. To obtain 18 $V\,t$ joules in T minutes, work must be done at the rate of $\frac{18\ V\,t}{60\ T}$, or $\frac{.3\ V\,t}{T}$, joules per second, or watts. In still air, when work has been supplied at this rate for T minutes, the desired temperature will have been attained; but if the air is being changed, it will be necessary to supply additional work at a certain rate to compensate for the loss of heat through ventilation. To maintain a constant temperature elevation of $t°$ F. in air changing at the rate of v cubic feet per minute, energy must be furnished at the rate of $\frac{18\,v\,t}{60} = .3\,v\,t$ watts. For the first T minutes, therefore, work must be done at the rate of $\frac{.3\,V\,t}{T} + .3\,v\,t$, or $.3\,t\left(\frac{V}{T} + v\right)$, watts, and afterwards at the rate of $.3\,v\,t$ watts for as long a time as the temperature elevation of $t°$ is to be maintained.

An electric heater for continuous heating should have at least two heating units, or resistance sections, both being used until the room is at the desired temperature, then one alone to maintain the temperature. The efficiency of an electric heater for warming rooms is practically 100 per cent., for the only loss of heat occurs by conduction through the supports of the heater to the wall or floor

39. Example of Room-Heating Estimate.—The applications of the foregoing principles are illustrated in the following example:

Example.—The air in a room 16 feet square and 10 feet high is changed three times an hour. The entering air has a temperature of 10° F. The temperature of the room is to be raised to 70° F. in half an hour and maintained at 70°. The walls, floor, and ceiling of the room are assumed to be perfect heat insulators. (*a*) What must be the capacity, in watts, of each section of a two-section electric heater for this room? (*b*) If the heater is to be operated on a 220-volt circuit, what must be the resistance of each section? (*c*) What current must each section carry? (*d*) If the heater is started at 7 A. M. and turned off at 10 P. M., what will be the daily cost of operation at 5 cents per kilowatt-hour?

Solution.—The volume of the room is $16 \times 16 \times 10 = 2{,}560$ cu. ft. The air is changed three times per hour, or once every 20 min.; therefore, the rate of change is $2{,}560 \div 20 = 128$ cu. ft. per min. The temperature of the air is to be raised 70−10=60° F. Using the symbols in Art. **38,** $V=2{,}560$, $v=128$, and $t=60$. Also, $T=\frac{1}{2}$ hr., or 30 min.

(*a*) One section of the heater must take

$$\frac{.3\,V\,t}{T}=\frac{.3\times 2{,}560\times 60}{30}=1{,}536 \text{ watts.}\quad \text{Ans.}$$

The other section must take

$$.3\,v\,t=.3\times 128\times 60=2{,}304 \text{ watts, approx.}\quad \text{Ans.}$$

During the first 30 min., while the room is heating up, energy must be supplied at the rate of 1,536+2,304=3,840 watts; at the end of 30 min., when the room has reached 70°, the 1,536-watt section may be switched off.

(*b*) In another Section, it is shown that watts=volts²÷resistance, or $P=\frac{E^2}{R}$, from which $R=\frac{E^2}{P}$. In this case, the value of E is 220, so the resistance of the 1,536-watt heater section will be

$$R=\frac{220\times 220}{1{,}536}=31.5 \text{ ohms, approx.}\quad \text{Ans.}$$

The resistance of the 2,304-watt section will be

$$\frac{220\times 220}{2{,}304}=21 \text{ ohms, approx.}\quad \text{Ans.}$$

(*c*) The current in the first section will be

$$I=\frac{P}{E}=\frac{1{,}536}{220}=7 \text{ amp., approx.}\quad \text{Ans.}$$

In the second section, it will be

$$\frac{2{,}304}{220}=10.5 \text{ amp., approx.}\quad \text{Ans.}$$

(*d*) The time from 7 A. M. to 10 P. M. is 15 hr. For the first 30 min. of this period the heater takes 1,536+2,304=3,840 watts, or 3.84 K. W.; for the remaining 14½ hr., 2.304 K. W. The total daily input to the heater is 3.84×.5+2.304×14.5=35 K.-W.-hr., nearly. At 5c. per K.-W. hr., the daily cost is 35×.05=$1.75. Ans.

40. Adaptability of Electric Heat for Rooms. According to the example of Art. **39,** the cost per day for heating a single room electrically is considerably above the cost of other heating methods, even at the low price for electrical energy of 1 cent per kilowatt-hour, which would reduce the cost to 35 cents per day. The use of electric energy for the continuous heating of rooms is usually confined to those places where cost is a relatively unimportant item in comparison with cleanliness or convenience, such as the staterooms of ships, street cars, etc. Small electric heaters are used quite extensively as auxiliaries to ordinary hot-water, hot-air, or steam systems, the electric heaters being employed temporarily and locally in such places as bathrooms and bedrooms.

WATER HEATING

CALCULATIONS

41. It requires energy supply at the rate of practically 18.34 watts to raise the temperature of 1 pint of water 1° F. in 1 minute. To raise V pints of water $t°$ F. in T minutes, using a heater whose efficiency is n, energy must be supplied at the rate, in watts, of

$$P = \frac{18.34\ V t}{T n} \qquad (1)$$

Conversely, energy supplied at the rate of P watts through a heater operating at an efficiency n will raise V pints of water $t°$ F. in a number of minutes equal to

$$T = \frac{18.34\ V t}{P n} \qquad (2)$$

The efficiency n is the ratio of the net heat absorbed by the water to the total heat equivalent of the energy supplied to the heating device.

42. If the efficiency is unknown it must be assumed. The value may vary from .60 for a disk heater with a separate vessel to .85 or .90 for a heater in which the vessel and heating element are combined in a single apparatus. In any case, the efficiency factor must take into account all heat losses, both from the heating element proper and from the vessel, in order to give the net heat supply to the water.

For melting ice or converting water into steam, allowance must be made for latent heat. (See Art. **11.**) Electric heat is rarely used for either of these purposes.

EXAMPLE.—(*a*) Assume that an electric heater has an efficiency of 85 per cent.; at what rate in watts must electrical energy be supplied to the heater in order to raise the temperature of 2 quarts of water from 50° F. to the boiling point in 20 minutes? (*b*) At 110 volts, what current will the heater take?

SOLUTION.—(*a*) The boiling point of water at atmospheric pressure is 212° F., and the value of t, formula **1**, Art. **41**, is $212° - 50° = 162°$. The other values to be substituted in the formula are: $V = 2 \times 2 = 4$; $T = 20$; $n = .85$. Then,

$$P = \frac{18.34 \times 4 \times 162}{20 \times .85} = 700 \text{ watts, nearly.} \quad \text{Ans.}$$

(*b*) The current at 110 volts will be $700 \div 110 = 6.4$ amp., approx. Ans.

ELECTRIC WATER HEATERS

43. Beyond small appliances for cooking there are not a great many electric water heaters in use. Household appliances designed especially for heating water are usually of either of two classes: *immersion heaters* and *self-contained heaters.*

Immersion heaters consist of an armored unit, sometimes cylindrical in shape and sometimes in the shape of a coil, which is submerged in the water to be heated until the desired temperature is attained. Immersion heaters for domestic use are of small capacity and may be used in any small vessel.

Self-contained heaters are those in which the vessel and heating unit are combined in a single apparatus. To this latter class belong many special appliances, such as chafing dishes, coffee percolators, tea kettles, etc.

44. In a device known as an **electric geyser,** the heating of the water is effected by the current traversing the water itself. Water flowing through the device is compelled to take a zigzag path among a series of plates of platinum foil that form the terminals by which current is led into and out of the water. Electric current passes only when water is flowing through the heater.

A type of immersion heater known as a **circulation water heater** is designed for use with the ordinary kitchen hot-water tank. The heating unit is of the armored type and is contained in a small auxiliary tank, or reservoir, which is piped to the kitchen tank.

HOUSEHOLD COOKING APPLIANCES

45. Advantages of Electric Cooking.—The American market contains a large variety of electrically heated household cooking appliances, from which may be selected a group of devices that will perform all the usual cooking operations. Such devices may be examined in the show rooms of central stations, in the stores of electrical supply dealers, and in the stores of many other dealers in household supplies.

The specific advantages of electric cooking over other methods may be briefly summarized as follows: Much of the cooking can be done on the dining-room table; so little heat is given out into the room during the cooking that there is no added discomfort during hot weather; the air is not vitiated by products of combustion, as in the case of the gas stove; the apparatus are clean and convenient.

46. Requirements of Electric Cooking Appliances. Household cooking appliances are usually designed according to either one of two systems: the *hot-plate system* or the *self-contained system.*

In the **hot-plate system,** one or more heating elements are used in connection with ordinary cooking vessels. In the **self-contained system,** each vessel has its own electrical heating element. The cost of apparatus for the hot-plate system is less than that for the self-contained type, and the hot-plate system has some advantages in simplicity of operation. The efficiency of hot-plate apparatus is, however, less than that of the self-contained devices; therefore, the higher the price of energy the greater is the advantage of the self-contained system in the matter of economy. A burn-out of the resistor in an appliance of the self-contained type is usually more annoying than a burn-out in a separate heating element. The self-contained appliance must also be designed so as to permit easy and thorough cleaning.

Electric ovens should distribute heat uniformly throughout the cooking space, and maintain a steady movement of hot air-currents in the proper directions to prevent uneven baking or roasting. Some means ought also to be provided for inspection of the baking or roast without opening the door of the oven. Glass doors meet this requirement, but they are rather expensive.

Cooking apparatus of all descriptions should be provided with some means of regulating the heat with considerable accuracy and through a considerable range of values.

Since electrical cooking apparatus will be handled by persons unfamiliar with the care of electrical machinery, the appliances should be durable and fool-proof; and, to prevent shocks, they should be immune to electrical breakdown. One of the greatest sources of trouble with household electrical heating devices lies in the connections and the flexible covered conductors leading to them. The flexible leads are liable to become twisted and kinked, the insulation wears off, and as a natural result, burnouts follow. On the whole, however, the apparatus of American manufacturers are sturdy and reliable.

47. Efficiency of Electric Cooking Appliances.—In order to compensate for the greater amount of heat obtainable from gas at the same cost, the highest possible efficiency reasonably obtainable is necessary in electric cooking appliances. The efficiency of apparatus for boiling, frying, etc., in which the basis is the transmission of heat to a liquid, such as water or fat, varies from 60 to 90 per cent., heaters of the self-contained type having the higher values. Accurate experimental determinations of electric-oven efficiency are difficult to obtain, but it may be quite safely stated that the electric oven is more efficient than the average gas oven.

ELECTROLYTIC FORGE

48. Principle.—An **electrolytic forge,** or *tempering bath*, Fig. 10, for heating by what is known as the **Hoho process** consists of a metallic-lined tank *c* containing water or a suitable solution *b*. The metal lining *d* is made the positive electrode of a direct-current generator and a piece of metal *a* to be heated is made the negative electrode, the circuit for the electric current being completed through a contact bar *e* and the solution. Upon the passage of current, the solution is decomposed, and the hydrogen gas liberated adheres to the submerged part of the metal. The gas introduces so much resistance to the passage of current between the solution and the metal that intense heat is developed at the contact surface, and the metal may be raised to the required temperature by regulating the current and the length of time the metal is submerged.

Lead is generally used for the tank lining, because the lead salts formed by the electrochemical action are insoluble, preventing a metallic deposit on the tool to be heated. A solution often used consists of 10 parts of washing soda and 1 part of borax, by weight, dissolved in enough water to give a specific gravity of about 1.17. The voltage is usually 110, and the current is regulated by means of a rheostat to a value depending on the area of the surface to be heated and the temperature required. The process is sometimes modified by bringing the tool in contact with only the surface of the liquid, so that the liberated hydrogen may ignite and aid in heating the metal.

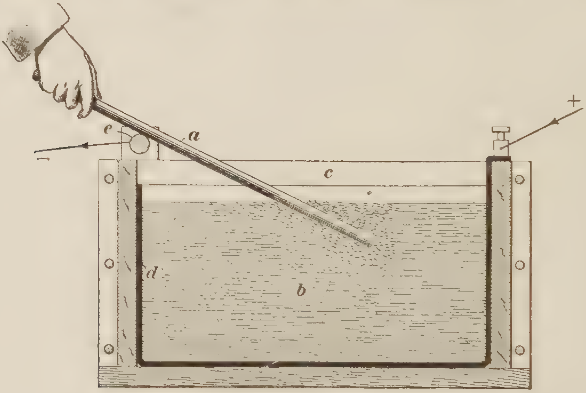


FIG. 10

49. Tempering by the Hoho Process.—By the Hoho process, metals can be tempered with a great degree of accuracy. The current can be adjusted until the submerged part of the metal is at the proper temperature and then shut off, leaving the metal in contact with cold water or tempering solution and thus tempering it. Any composition it is desired to use in tempering can be dissolved in the liquid. The heating is under such perfect control that the tempering can be carried to any desired depth from the surface of the metal. Suitable insulating shields placed over parts of the metal prevent the development of heat on surfaces that are not to be tempered. Large surfaces, such as the wearing surfaces of steel rails, steel axles, shafting, cannon, etc., can be tempered by exposing small parts at a time to the action of the current and the tempering bath, the remaining parts being covered with shields.

By the Hoho process, metals are heated in an envelope of hydrogen gas, which prevents oxidation and thus makes this process very desirable for all operations where oxidation is objectionable. Soldering is one such operation, and metals that are very difficult to solder by any other process can be easily soldered by using an electrolytic forge.

THAWING FROZEN WATER PIPES

50. General Method.—The process of thawing a frozen water pipe by electricity consists in heating the pipe by setting up an electric current in it. Alternating current is generally used, because, by the use of a transformer, almost any amperage can be easily obtained. In cities and towns where the winters are severe, central stations sometimes provide special transformers mounted, together with the necessary cables, terminal clamps, measuring instruments, rheostats, etc., on a wagon, a sled, or an automobile.

When a request is made for the services of the pipe-thawing outfit, it is hauled to the desired place, the terminals of the primary coil connected to the high-voltage lighting circuit, the terminals of the secondary coil to the frozen section of the pipe, one at each end, and an electric current of the proper value turned on.

51. Pipe-Thawing Data.—The current for pipe thawing should be suitable for the work to be performed; a large pipe of low resistance will require a larger current than a small pipe. Too large a current may injure the pipe; hence, it is better to use a more moderate current for a longer period of time. Theoretically, the length of time required to produce running water in pipes that are frozen solid varies inversely as the square of the currents used.

Table VI gives figures obtained in practice, showing the diameters and lengths of frozen pipes, and the amperes, volts, and time required to produce running water in each size. These results are probably a fair sample of what may be obtained in practice, but are too inconsistent to permit of making definite rules to be followed in all cases. For example, a 1-inch pipe 700 feet long embedded in solidly frozen ground required 175 amperes for 5 hours, while another pipe of the same diameter and 600 feet long, but much less solidly frozen, required only 60 amperes for 1 hour. It is very seldom that an ordinary house pipe requires more than from 30 to 50 volts and 300 amperes.

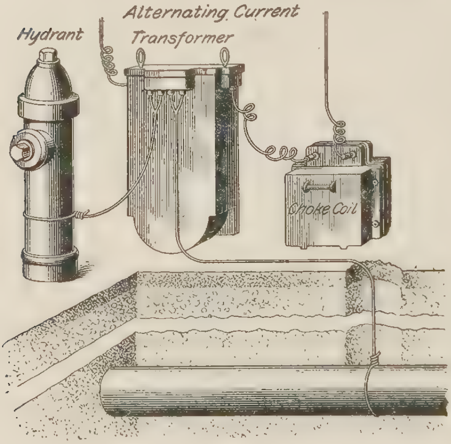


FIG. 11

52. Thawing Transformers.—The thawing transformer should be compact and easily portable. If specially designed, the transformer usually has a large magnetic leakage, so that with heavy secondary currents there will be a considerable drop of the secondary voltage; in fact, such a transformer may be short-circuited for several minutes without injury. This design makes the transformer so bulky that it is used only for work requiring fairly low secondary voltages; for

TABLE VI
PIPE-THAWING DATA

Diameter Inches	Length Feet	Material	Amperes	Volts	Time Minutes
½	50	Lead	250	15	5
½	50	Iron	250	20	5
½	70	Iron	300	16	15
½	100	Iron	150	20	45
⅝	180	Lead	185	35	15
¾	40	Iron	300	50	8
¾	60	Iron	320	110	25
¾	75	Iron	100	50	5
¾	80	Iron	300	110	23
¾	100	Iron	135	55	10
¾	100	Iron	300	110	11
¾	150	Lead	250	50	12
¾	200	Iron	110	50	6
¾	200	Iron	120	50	1
¾	240	Iron	250	52	30
¾	250	Iron	120	50	10
¾	250	Iron	400	50	20
¾	380	Iron	300	30	10
1	45	Iron	140	220	17
1	90	Iron	280	110	10
1	100	Iron	175	220	15
1	150	Iron	200	40	20
1	150	Iron	280	110	120
1	220	Iron	60	105	75
1	250	Iron	400	50	20
1	250	Iron	500	50	20
1	600	Iron	60	50	60
1	700	Iron	175	55	300
1¾	130	Iron	340	110	90
2	20	Iron	2,000	6	180
2	50	Iron	500	50	120
2	60	Iron	160	50	4
2	300	Iron	250	52	150
4	800	Iron	300	50	180
6	400	Iron	800	110	70
8	700	Iron	1,000		2,400

higher voltages, an ordinary lighting transformer with a choke coil in series with the primary circuit is used. The choke coil accomplishes the same object as the magnetic leakage in the special transformers.

53. Connections.—There should be very little resistance in the secondary circuit; that is, the secondary mains should be short, and all contacts should be made clean and secure. In thawing house piping, one secondary lead is usually connected to a faucet and the other to the pipe where it enters the house, to a hydrant, or to a faucet in a neighboring house, the object being to send the current through all the frozen section. In thawing street mains, connections may be made to two hydrants or to one hydrant and the pipe beyond the frozen section, as shown in Fig. 11.

ELECTRIC WELDING

54. Electric welding is a process in which an electric current furnishes the heat to bring metals to a welding temperature. There are two fundamental electric welding processes, the *Thomson process* and the *Bernardos*, or *arc*, *process*. The Thomson process is the more widely used.

THOMSON PROCESS

55. Principle.—The **Thomson process of electric welding** consists in causing a heavy current of electricity at a low voltage to pass through the abutting ends of the pieces of metal to be welded while mechanical pressure is applied to force the parts together. The junction, being the part of the electric circuit offering the greatest resistance, is heated, and, as the metal on each side of the junction softens, a complete weld is effected by mechanical pressure. Alternating current is used, because a direct current of high amperage and low voltage is difficult to obtain.

56. Example of Welding Machine.—Welding machines operating on the Thomson principle are made in a large variety of designs and sizes, from small, hand-operated machines for welding small bars to large, automatic machines for complicated work, such as welding wire mesh fences.

One of the more simple hand-operated types, most frequently used for welding iron bands, is illustrated in Fig. 12. A flat iron hoop is shown in position for welding, but different forms of clamps permit the handling of a variety of work. The transformer is contained in the base *a* of the welder, and the work is held by clamps *b* and *c* operated by handles *d* and *e*. A lever *f* and a toggle *g* serve to force the clamp *c* toward *b* when the proper heat is attained. Water is circulated through the clamps by means of pipes *h* and *h′*. The pipe *h′* is a piece of rubber hose, which affords the necessary flexibility and also prevents the passage of current between the clamps by way of the pipe. The current can pass from one clamp to the other either by crossing the joint to be welded or by going around the unjointed part of the hoop; much the larger portion takes the shorter path across the joint.

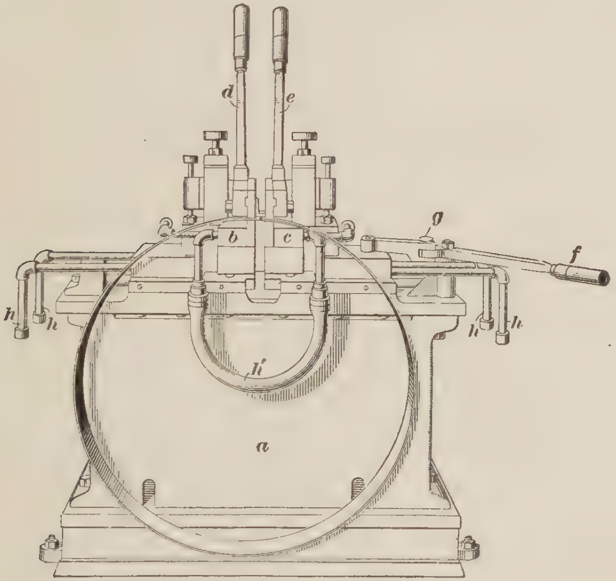
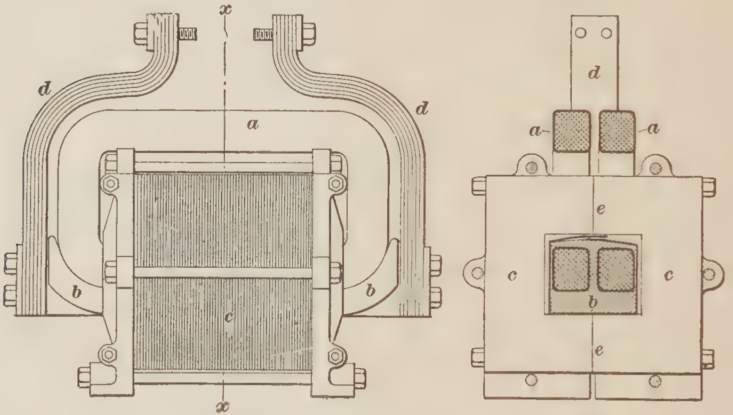


Fig. 12

57. Example of Welding Transformer.—A typical welding transformer such as is used in welders of small and medium size is shown in Fig. 13, (*a*) being a front view, and (*b*) a sectional view. The sectional view shows the transformer as though it were cut squarely in two at the line *x x* of Fig. 13 (*a*). The reference letters in both views have the same significance.

The three essential parts of the transformer are the primary coils *a*, the cast-copper secondary *b*, and the laminated-iron core *c*. Each end of the secondary *b* is planed smooth and tapped for clamping the flexible copper leads *d*. The core is split, as indicated at *e*, Fig. 13 (*b*), to facilitate dismantling. Where the primary coils pass through the core, they are embedded in the **H**-shaped secondary casting. Outside of the core, the primary coils are exposed for more rapid heat dissipation. The secondary leads are built up of thin sheet copper to the required cross-section in order to obtain flexibility. Holes are drilled through the ends of the leads for bolting directly to the heavy copper blocks, upon which the dies and clamping mechanism of the welder are mounted. The leads retain about the shape and position shown in Fig. 13 (*a*). Just over the primary coils is fastened a shield (not shown) of brass and fiber to protect the transformer from chips and molten metal thrown off in making a weld.



(*a*) FIG. 13 (*b*)

58. Voltage Regulation for Welders.—Secondary voltage regulation in transformers having several primary coils is obtained by connecting the coils in multiple, in series, or in series-multiple by one or more double-throw switches. A finer secondary voltage adjustment may be obtained by tapping the winding of one or more primary coils and connecting the taps to contact-blocks over which a movable contact slides, as in the case of an ordinary rheostat. In some cases, a variable reactance, or choke, coil is interposed in the primary circuit, and regulation is secured by cutting in more or less of the winding by the method just mentioned.

TABLE VII

ENERGY REQUIRED FOR BUTT WELDING

Diameter Inches	Area Square Inches	Approximate Kilowatts	Time for Weld Seconds	Approximate Kilowatt-Hours 1000 Welds
$\frac{1}{4}$	.05	4	2	2
$\frac{3}{8}$	.11	6	3	5
$\frac{1}{2}$	.20	9	6	15
$\frac{5}{8}$	.31	12	10	30
$\frac{3}{4}$	.44	15	15	65
$\frac{7}{8}$	.60	18	18	90
1	.79	20	20	113
$1\frac{1}{8}$	.99	25	24	167
$1\frac{1}{4}$	1.23	30	33	275
$1\frac{1}{2}$	1.77	38	40	422
$1\frac{3}{4}$	2.41	48	48	640
2	3.14	60	60	1000

59. Energy Required for Thomson Process.—The primaries of electric welding transformers are operated on single-phase alternating currents of voltages between 100 and 500 and frequencies from 40 to 60 cycles per second. In the secondary circuit, a low-voltage current as high as 60,000 amperes per square inch may be necessary in welding some metals. A low frequency reduces the inductive effects.

Within limits, the time required for making a weld varies inversely with the amount of power supplied; that is, the greater the power the shorter will be the time, and the less the power the longer will be the time. Metals that are deteriorated by being heated, such as copper, brass, and tool steel, must be welded rapidly. The pressure must be great enough to crowd out from the weld all metal harmed by the heat. Tests have shown that from 70 to 75 per cent. of the power supplied is actually used in making the weld, so that there is comparatively little heat wasted. Although there is a great loss of heat in the

TABLE VIII

ENERGY REQUIRED FOR SPOT WELDING

Gauge of Sheet Steel	Thickness Fraction of an Inch	Thickness Decimal Part of an Inch	Approximate Kilowatts	Time in Seconds to Make a Weld	Approximate Kilowatt-Hours 1000 Welds
28	1-64	.015625	5	.3	.45
26	3-160	.018750	6	.4	.65
24	1-40	.025000	7	.5	1.00
22	1-32	.031250	8	.6	1.35
20	3-80	.037500	9	.7	1.75
18	1-20	.050000	10	.8	2.25
16	1-16	.062500	12	.9	3.00
14	5-64	.078125	14	1.0	3.90
12	7-64	.109375	16	1.3	5.80
10	9-64	.140625	18	1.5	7.50
9	5-32	.156250	20	2.0	11.20
8	11-64	.171870	23	2.5	16.00
7	3-16	.187500	25	3.0	21.00
6	13-64	.203120	28	4.0	31.00
5	7-32	.218750	30	5.0	42.00
4	15-64	.234370	33	6.0	55.00
3	1-4	.250000	35	7.0	68.00

steam engine, and also some loss in the dynamo, it has been found that the fuel cost for electric welding is but little more than for welding by the ordinary process, because in the electric process, nearly all the heat is applied just where it is wanted.

Table VII shows the approximate energy necessary for butt welding various sizes of round iron or steel bars. Table VIII gives the approximate energy for spot welding sheet iron of various thicknesses. In spot welding, each *spot* performs the service of a rivet.

60. Advantages of the Thomson Process.—Electric welding by the Thomson process is adapted to some forms of work where it would be difficult to apply the heat by any other method. In addition to this, it possesses several marked advantages over other methods. Electric welds are homogeneous, because when metals are heated by the electric current the central part gets hot first, while welds made by externally applied heat are often faulty at the center. There is almost absolute control over the heat and the heat is localized at the weld. The metal, while heating, is visible in the open air; hence, it may be closely watched. Skilled labor is unnecessary in most cases. The welder is always ready at the turn of a switch. The process, in general, is clean, safe, accurate, and rapid.

ARC PROCESS

61. Principle.—The **Bernardos,** or **arc, process of electric welding** consists in the utilization of the heat of a direct-current arc. The metals to be welded are usually made positive; a carbon rod, negative. The arc is struck by momentarily touching the work with the carbon and drawing out the arc to the required length. The heat of the arc quickly raises the work to welding temperature, and the weld is completed by hammering or rolling. Scrap metal is usually fed into the arc to provide the additional metal that may be necessary for a perfect weld.

62. Description.—The arc process in its simple form is illustrated in Fig. 14. The anvil *a*, upon which rests the piece *b* to be welded, is connected to the positive pole of a source of direct current. The arc is drawn between *b* and the carbon rod *c*. A variable resistance *d* is used to adjust the current. A more important function of this resistance is its action as a ballast, like the series resistance coil in an arc lamp. Any tendency of the current to vary causes a corresponding change in the drop of potential in the resistance, thus tending to maintain a uniform current in the arc under given conditions. A flexible cable passing through an insulating handle makes connection with the carbon.

The service voltage usually employed in the arc process is between 100 and 130, the arc requiring from 80 to 100 volts. The length of the arc varies from 1 to 3 inches, according to the class of work. The current may reach several hundred amperes.

The polarity of the work is of importance, because a suitable arc between some metals and carbon can be maintained with only one direction of current. The direction is not the same for all metals, a negative carbon being required for some metals and a positive carbon for others.

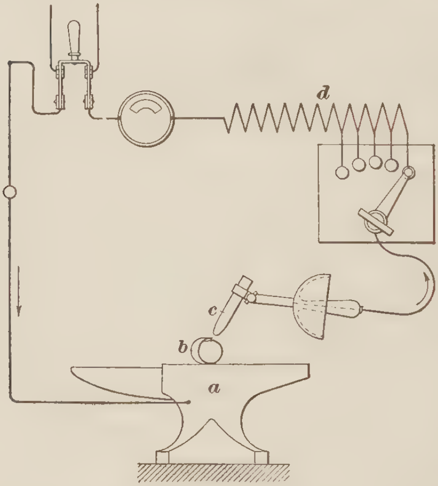


FIG. 14

It is necessary to protect the hand and the eyes of an operator from the intense rays of the arc. The hand is protected by a shield on the handle that holds the carbon. To protect the eyes, the work should be viewed through dense ruby glass or dense smoked glass. In very heavy work, a hood completely covering the operator's head, heavy gloves for his hands, and shields for other parts of his body; are necessary to protect him from the intense heat.

MISCELLANEOUS USES OF THE ELECTRIC ARC

63. Arc brazing is a variation of the arc-welding process. It consists of the employment of two carbons, a positive and a negative, held in one holder at an angle of from 45° to 90°. The arc is started by momentarily bringing the carbons together. With the carbons at an angle, the magnetic field set up by the current is more dense between them, so that the arc is deflected away from the tips. This deflected arc is employed in brazing.

64. Filling Blowholes in Castings.—The electric arc is useful in filling blowholes in castings. The casting to be treated is first heated to a dull red, to prevent harmful strains due to greatly unequal temperatures; then the arc is applied. The arc may be formed between the casting and a carbon rod, or a deflected arc between two carbons may be used. The metal used to fill the holes may be introduced into and melted by the arc, or, when one pole is connected to the casting to be filled, the other pole can be connected to an electrode of the proper metal for the filling.

65. Wrecking Structural Ironwork.—The electric arc may be used to wreck structural iron or steel in construction work. Either direct or alternating current may be used. One side of the circuit is connected to the work, and the other is connected directly to a carbon electrode. The heat of the arc burns away the metal where desired, until either a complete cut is made or the metal is sufficiently weakened to be easily broken. The carbon electrode is usually clamped between copper plates about 4 or 5 inches square and $\frac{1}{2}$ inch thick. A sweated connection of the conductor to these plates cannot be used on account of the intense heat. The operator must wear gloves and a mask of asbestos to protect himself from the heat, and dense black goggles to protect his eyes from the rays of the arc.

ELECTRIC ANNEALING

66. Electric annealing, another application of electric heating, is a process by which parts of steel plates or castings on which it is desired to perform machine work are softened. The heavy secondary terminals of a special transformer are placed on the part to be softened, as shown in Fig. 15, and a large current is sent through it. The part is thereby heated and softened, but other parts of the casting are not affected. Although entirely practicable, electric annealing is not employed to any great extent. One of the chief applications of the method is for the localized annealing of armor plate. Heat for annealing can be supplied by some types of electric welders when furnished with special terminals.

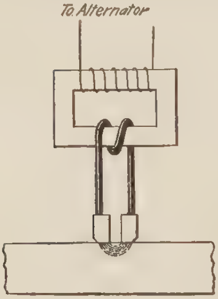


FIG. 15

ELECTRIC FURNACES

DEFINITIONS AND CLASSIFICATION

67. An **electric furnace** is a furnace in which electric current is used solely for its heating effect. It is to be distinguished from an *electrolytic furnace*, in which the current is used primarily for its decomposing effect. Heat is necessarily generated in the electrolytic furnace, but its generation is incidental and its rate of generation may or may not be sufficient to keep the furnace at the desired temperature. An electric furnace may operate on either direct or alternating current; the electrolytic furnace necessarily runs on direct current only.

Either of the two fundamental methods of converting electric energy into heat may be employed in an electric furnace. *Arc furnaces* are those in which the heat is generated by producing an electric arc. *Resistance furnaces* are those in which the heat is generated by the passage of an electric current through a resistor. Furnaces employing both methods of energy conversion are called *combination furnaces.*

The choice between these fundamental types depends primarily on the nature of the chemical reaction involved and the properties of its products. In the refining of steel, for instance, the resistance type is usually employed, because the introduction into the steel of carbon from the electrodes of an arc furnace may injure the quality of the steel.

68. Arc furnaces are sometimes divided into two classes, *direct-arc furnaces* and *indirect-arc furnaces.* In the former, the arc plays directly on the material to be heated; in the latter, the material is not directly exposed to the arc, but receives the heat by reflection from the roof and walls of the furnace. In some furnaces there is combined direct and indirect heating.

69. A simply constructed **direct-arc furnace** is illustrated in Fig. 16. A carbon crucible *a*, surrounded by refractory material *b*, rests on a plate *c* of carbon or metal to which one terminal is connected. The crucible thus forms one electrode. The other electrode consists of a carbon rod *d*, which may be raised or lowered by means of the screw *e* and the hand wheel *f*. The material to be treated is placed in the crucible and the arc formed between the material and the rod *d*. When the desired result is produced the charge, if liquid, may be tapped off through an opening *g*.

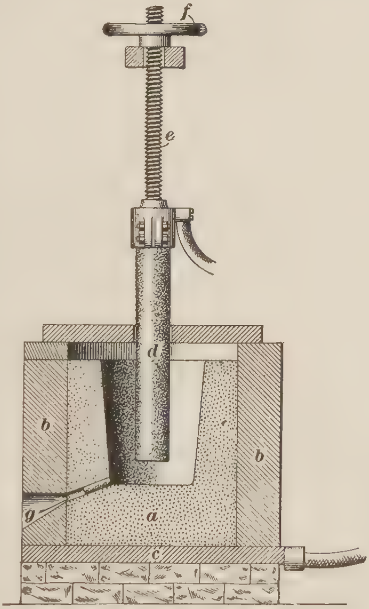


FIG. 16

This type of furnace was originally used by its inventor, Siemens, to melt steel. The steel was heaped in the crucible and the movable electrode lowered into contact with the top of the heap. When current was allowed to pass, considerable heat was generated without the use of an arc, owing to the contact resistance of the irregular pieces of steel. As soon as the steel began to soften, the contact resistance disappeared, and to maintain the temperature, an arc with a difference of potential of about 40 volts was drawn by raising the movable electrode.

70. The **indirect-arc furnace** in its simple form is illustrated in Fig. 17. It consists of a crucible *a* of refractory material surrounded by firebrick and covered by a fireclay slab *b*. Carbon rods *c* and *d* enter from each side and form the electrodes. The arc is started either by sliding one carbon in until it touches the other and then withdrawing it, or by placing a very small carbon rod, say about $\frac{1}{16}$ inch in diameter, between the carbon points before turning on the current; when the current is turned on, the small rod will very soon burn out and the arc will start.

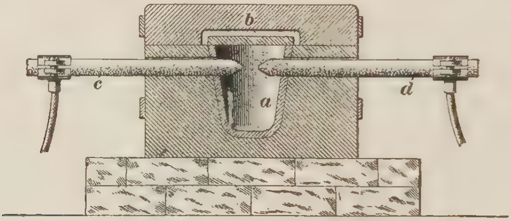


FIG. 17

Material placed in the bottom of the crucible *a* is heated by radiation and by reflection from the top of the crucible, which is usually rounded out in order to throw the reflected heat more directly on the material.

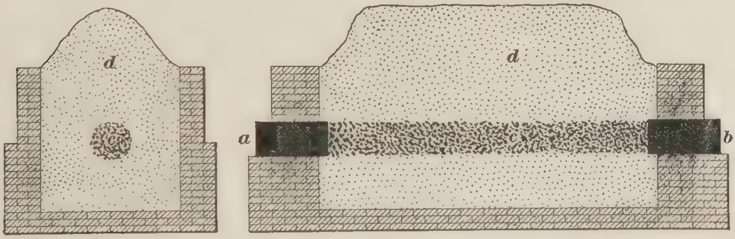
The **Stassano furnace** is an industrial electric furnace designed on the indirect-arc principle. It uses three electrodes arranged at the top of the furnace and operates with three-phase alternating currents. The arcs among the three electrodes heat the metallic bath below by radiation.

RESISTANCE FURNACES

71. Resistance furnaces are of two fundamental types: those employing a special resistor, usually carbon, and those in which the charge, or material under process, is itself a conductor and forms the resistance.

In smaller furnaces for work that does not require very high temperature, metallic resistors, such as are used in domestic appliances, may be employed. Resistors of carbon may take the form of rods, tubes, or granules of various sizes, depending on the design of the furnace. Kryptol and silundum are also used, the latter usually in the form of rods.

72. Carborundum Furnace.—A resistance furnace of the first class, invented by Acheson for the manufacture of carborundum, is illustrated roughly in Fig. 18, (*a*) being a cross-section, and (*b*) a longitudinal section. The terminals *a* and *b* are large carbon blocks clamped in place by iron plates to which the cables that conduct the current to the furnace are connected. The resistor *c* is composed of fragments of carbon. The resistance of the carbon and the contact resistance between the fragments are both utilized in establishing a temperature that reaches a value between 7,000° and 7,500° F.



(*a*) FIG. 18 (*b*)

The heat generated by the current through the resistor causes a chemical union in a mixture *d* of coke and sand, forming silicon carbide, known commercially as *carborundum*. When the reaction is complete, the side walls, which are of temporary structure, are taken down and the carborundum removed. A new resistor is necessary each time the furnace is charged.

The inside dimensions of the furnace are about 5 feet by 16 feet. Electrical energy is supplied to the furnace at a rate of about 1,500 kilowatts for 36 hours, a total consumption of about 54,000 kilowatt-hours per charge. At the start, the voltage is about 200, which is decreased to about 125 at the end of the run.

73. Induction Furnace.—In Fig. 19 is shown a horizontal section of a resistance furnace in which the charge itself forms the resistor. This furnace, designed for refining steel and known commercially as the **Röchling-Rodenhauser combination furnace,** is a type of induction furnace, in which the current in the charge is set up by electromagnetic induction, as in a transformer. The primary coils are shown at *a* around the core *h*. Part of the secondary current, induced entirely in the charge itself, passes through paths $c\,d$ and $c_1\,d$; another part, induced in large copper secondary windings, *b*, terminating in steel plates *e* and e_1, passes through part *d* only of the charge. The lining *g* covering the plates becomes a conductor when hot. The directions of the secondary currents during one alternation are represented by the arrows in the illustration. The walls *f* of the furnace are made of highly refractory material to withstand the intense heat.

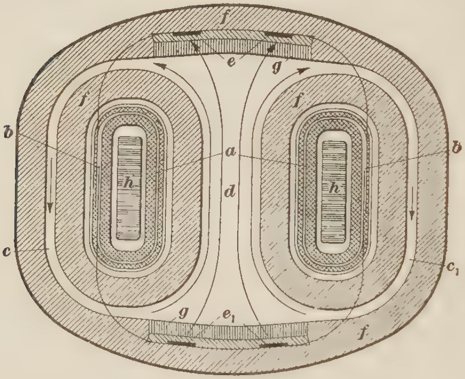


Fig. 19

The object of the auxiliary secondary windings, *b*, Fig. 19, is to reduce the magnetic leakage and thus improve the efficiency and power factor over a simple induction furnace without such windings. Earlier types of induction furnaces did not operate successfully on current of a frequency greater than 15 cycles per second, but furnaces with the auxiliary secondaries are operated on 25-cycle systems, and even on 60-cycle systems, with fairly good power factor. The furnace illustrated in Fig. 19 operates on single-phase current, but similar furnaces are made for three-phase currents.

The induction principle is also applied to some types of small electric heaters in which the secondary of the transformer is a metal shell of wrought iron used as a resistor.

74. Miscellaneous Resistance Furnaces.—The **Cowles furnace** operates on somewhat the same principle as the Acheson furnace. The object of the Cowles furnace is the reduction of metallic oxides by mixing them with granular carbon and placing the mixture between two electrodes. Here the carbon acts as a chemical reducing agent, as well as a resistor.

75. For small laboratory furnaces a solid rod of carbon may be used instead of the granular carbon of the Acheson furnace. In the **tube furnace,** a tube of carbon, instead of a rod, is used, the material to be treated being placed inside of the tube.

In another special type of resistor furnace the charge is heated by radiation from a resistor or group of resistors placed above it.

A simple furnace readily constructed may be made by embedding a crucible in kryptol or other granular resistance material contained in a sort of vat made of refractory material. The kryptol may surround all the crucible except the cover. Current is lead through the kryptol from carbon or graphite terminals in opposite sides of the vat.

76. In a type of **electric hardening furnace,** in which a constant, uniform temperature is needed for heating tools to be tempered or hardened, the resistor consists of a bath of a fused metallic salt. The tools are heated by immersing them in the molten bath, which is contained in a crucible of refractory material. Single-phase alternating current is sent through the bath between two iron electrodes. The salt, when cold, is a solid and a non-conductor; therefore, melting must be started by using a temporary resistor of carbon rods placed in a channel chipped in the top of the bath. The temperature is regulated by a dial-switch controlling the number of active turns in the primary of a transformer that is part of the furnace outfit. Direct-current cannot be used for this furnace, on account of electrolysis.

COMBINATION FURNACE

77. The **Héroult steel furnace** is an example of an electric furnace that may be classed as a combined arc and resistance furnace. The steel to be refined lies on the hearth of the furnace and is covered with a layer of slag. Two carbon electrodes are suspended vertically through the top of the furnace. The furnace is started by striking two arcs between the surface of the slag and the electrodes. Current then passes from one electrode through the slag and out through the other electrode by way of the two arcs. The heat of the arcs and the heat due to the passage of current through the slag are used in the furnace operation. If a lower heat is desired, the electrodes may be lowered until their ends are immersed in the molten slag, in which case the furnace operates on the resistance principle only. The Héroult furnace is also made with three electrodes adapted for operation on three-phase alternating currents.

REGULATION OF ELECTRIC FURNACES

78. The simplest way to regulate the heat of an electric furnace is to regulate the supply of electric energy. In an arc furnace, this is accomplished by moving the electrodes, either by hand or automatically, thus varying the length of the arc. In a resistance furnace the current through the resistor is varied by means of rheostatic devices or by regulating the generator voltage. Water rheostats are convenient for use with resistance furnaces.

ADVANTAGES OF ELECTRIC FURNACES

79. The chief advantages of the electric furnace over the combustion furnace are the higher temperatures attainable and the easier and better control of the conditions of operation. The maximum temperature attainable in a combustion furnace is about 2,000° C. (3,600° F.), and in an electric furnace a temperature of 3,500° C. (6,300° F.) is possible. Many chemical reactions possible in the electric furnace will not take place at the temperature of the ordinary combustion furnace. In the electric furnace, it is also possible to maintain complete control over the temperature, the chemical nature of the atmosphere in the furnace, etc. A control of such conditions is essential to the success of many chemical and metallurgical processes.

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NOTE.—In this Volume, each Section is complete in itself and has a number. This number is printed at the top of every page of the Section in the headline opposite the page number, and to distinguish the Section number from the page number, the Section number is preceded by a section mark (§). In order to find a reference, glance along the inside edges of the headlines until the desired Section number is found, then along the page numbers of that Section until the desired page is found. Thus, to find the reference "Acheson furnace, §44, p41," turn to the Section marked §44, then to page 41 of that Section.

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